Recent progress and future prospects for high energy density experimental physics

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American Physical Society
Division of Plasma Physics
Orlando, FL
Nov 11-15, 2002

*This work was performed under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory under contract No. W-7405-ENG-48.

Summary

- **Significant advances in high energy density physics have occurred over the last six years**
- **The ability to make precise measurements in new regimes allows comparion with models**
  - *Hugoniot equation-of-state*
  - *Materials science at high pressure*
  - *Hydrodynamics*
  - *Radiation transport*
- **New facilities will expand access to high energy density regimes**

Regimes of high energy density are typically associated with material energy density $\geq$ 1 MBar

- **Energy density and pressure have the same units**

$$\text{Energy density} = \frac{\text{Energy}}{\text{Volume}}$$

$$\text{Pressure} = \frac{\text{Force}}{\text{Area}} = \frac{\text{Force} \times \text{distance}}{\text{Area} \times \text{distance}} = \frac{\text{Energy}}{\text{Volume}}$$

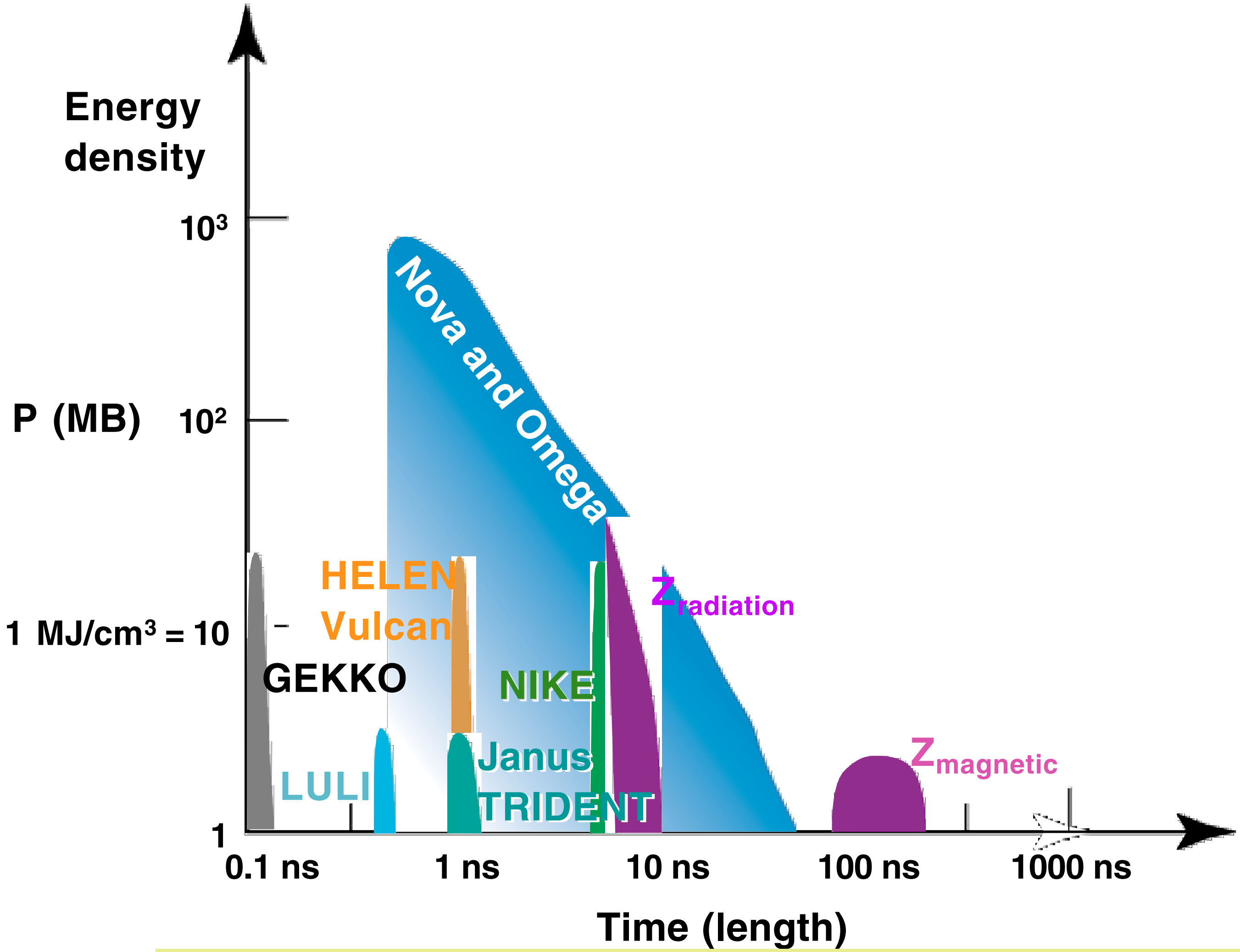
- **~ 1 Mbar is the energy density required to compress material**

$$\text{Energy density} = \frac{\text{Energy}}{\text{Volume}} = \frac{\text{Energy of Bohr atom}}{(\text{Bohr diameter})^3}$$

$$\sim \text{few MBar}$$

Bulk modulus ~ 1/compressibility ~ 1 MBars

Laser and pulsed power facilities access high energy density regimes



Most of these facilities were built for ICF
They can also be used for high energy density physics

Rosen, Phys Plas, 3, 1803 (1996)

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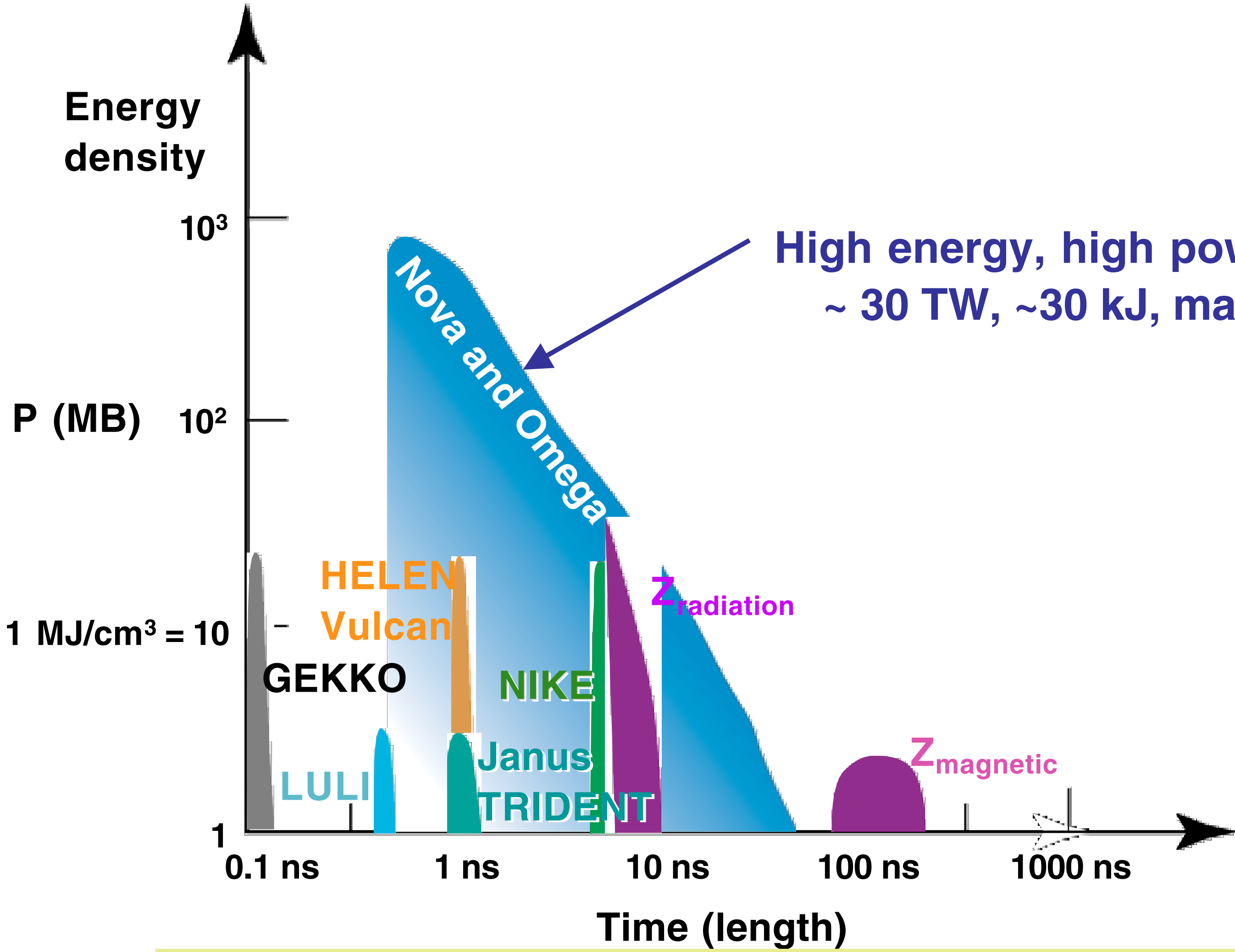

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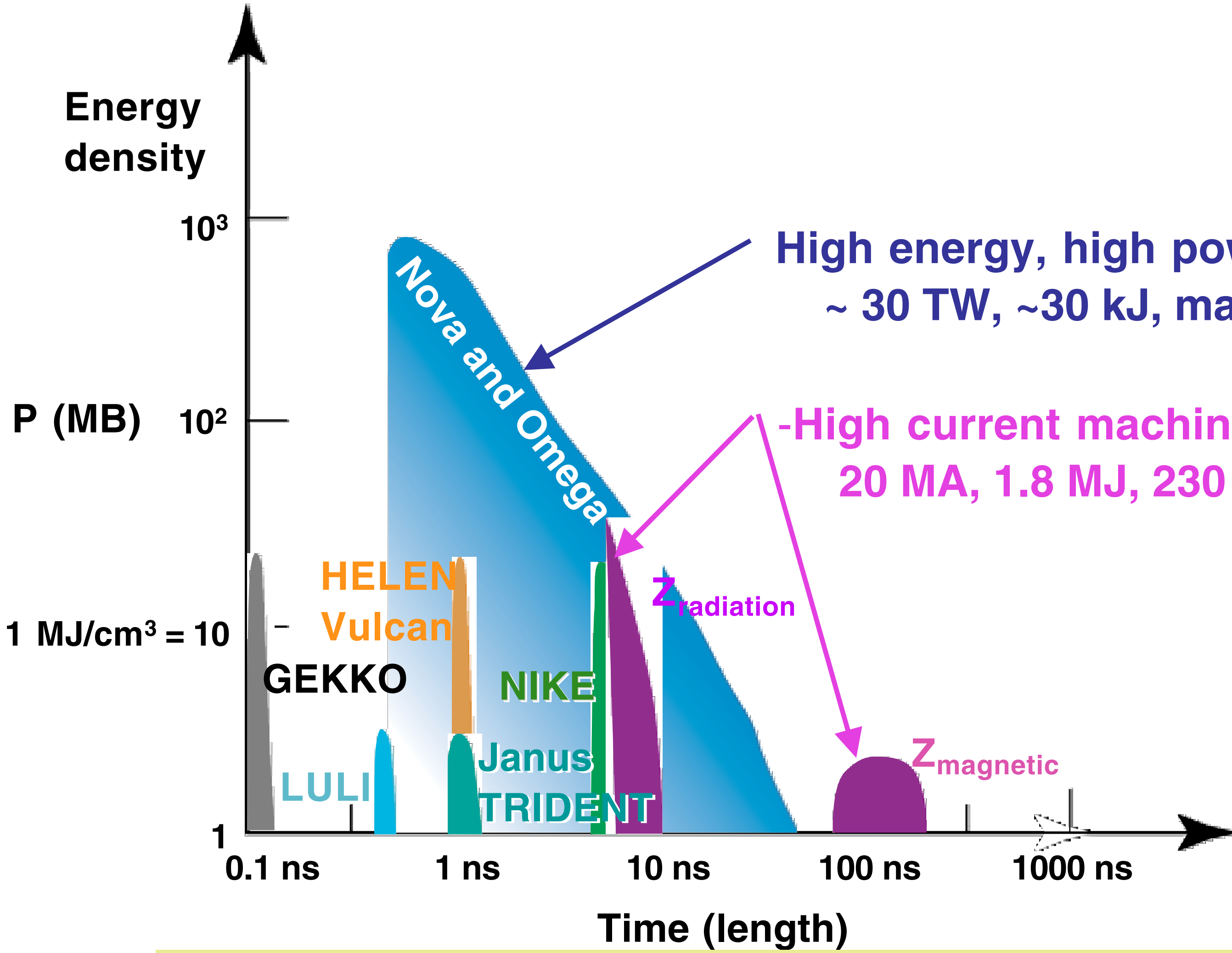

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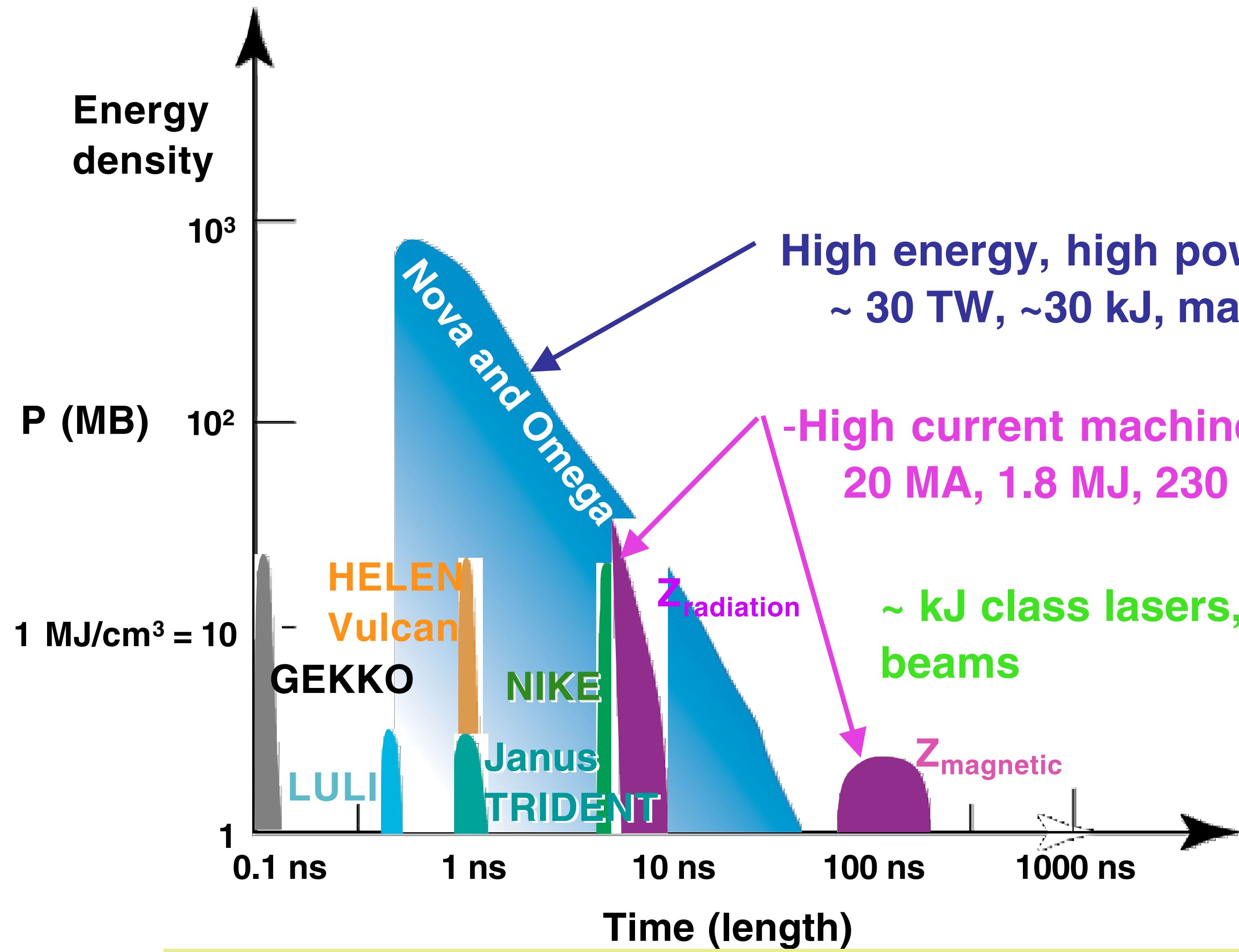

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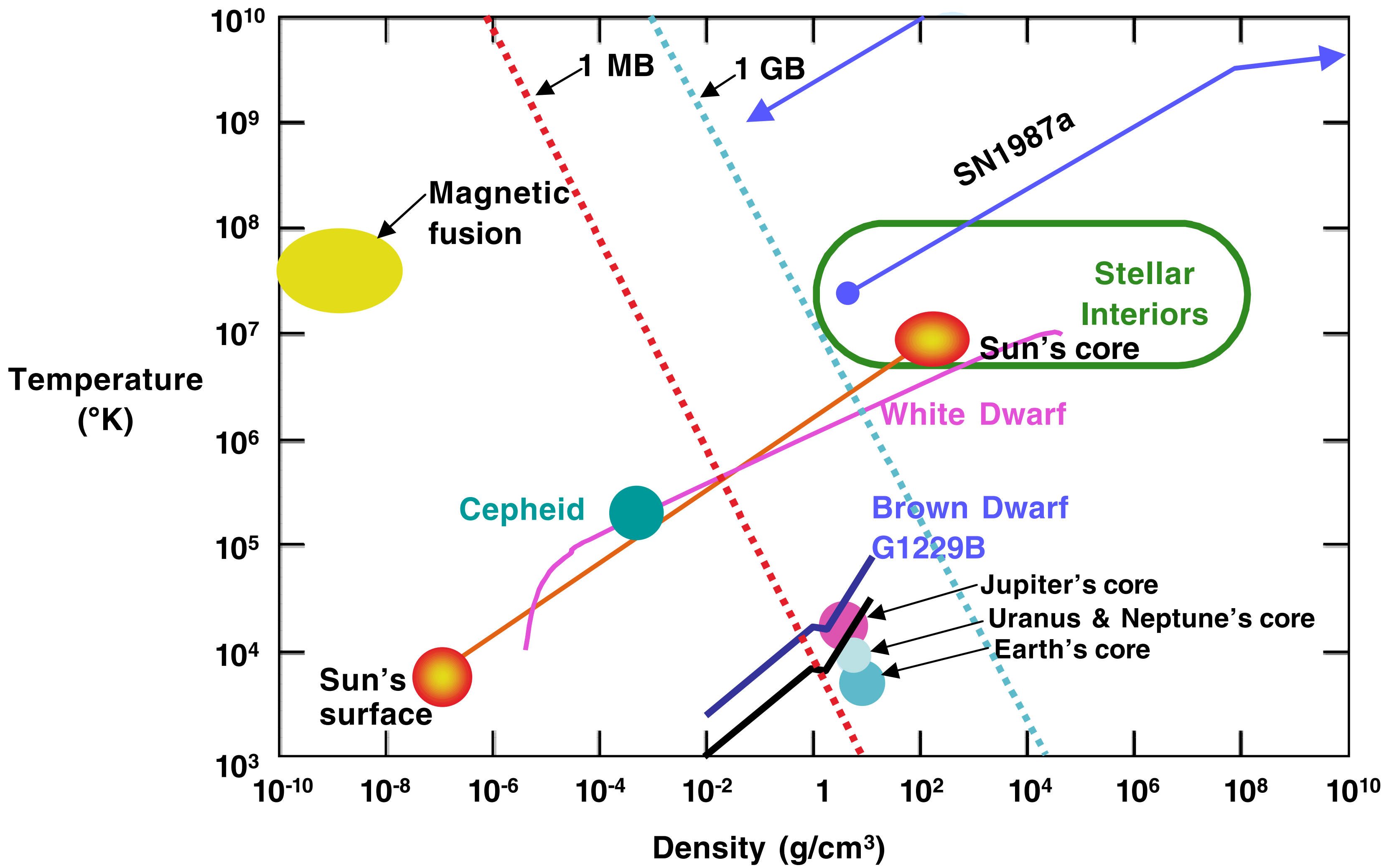
High energy density conditions exists in planets and stars



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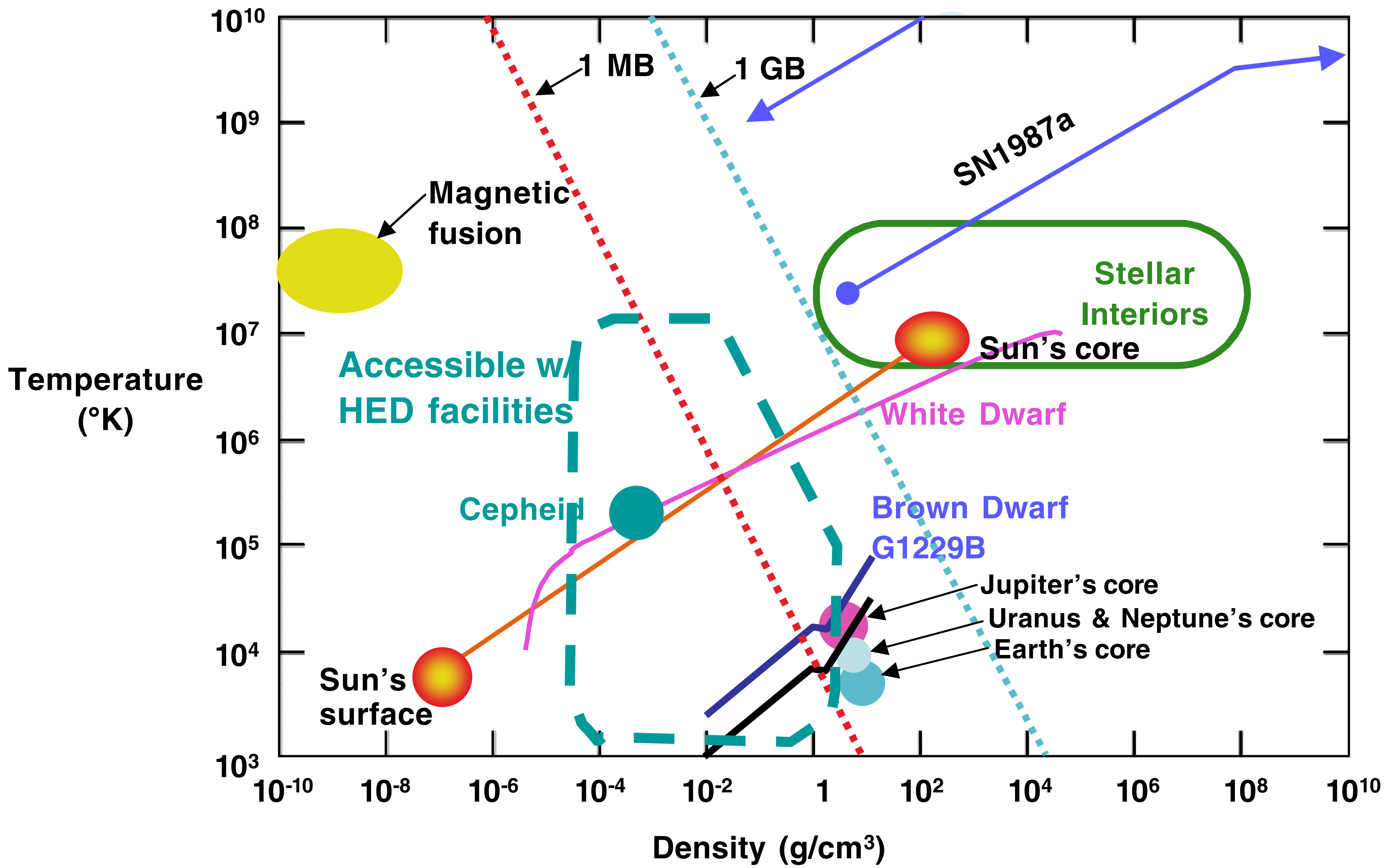
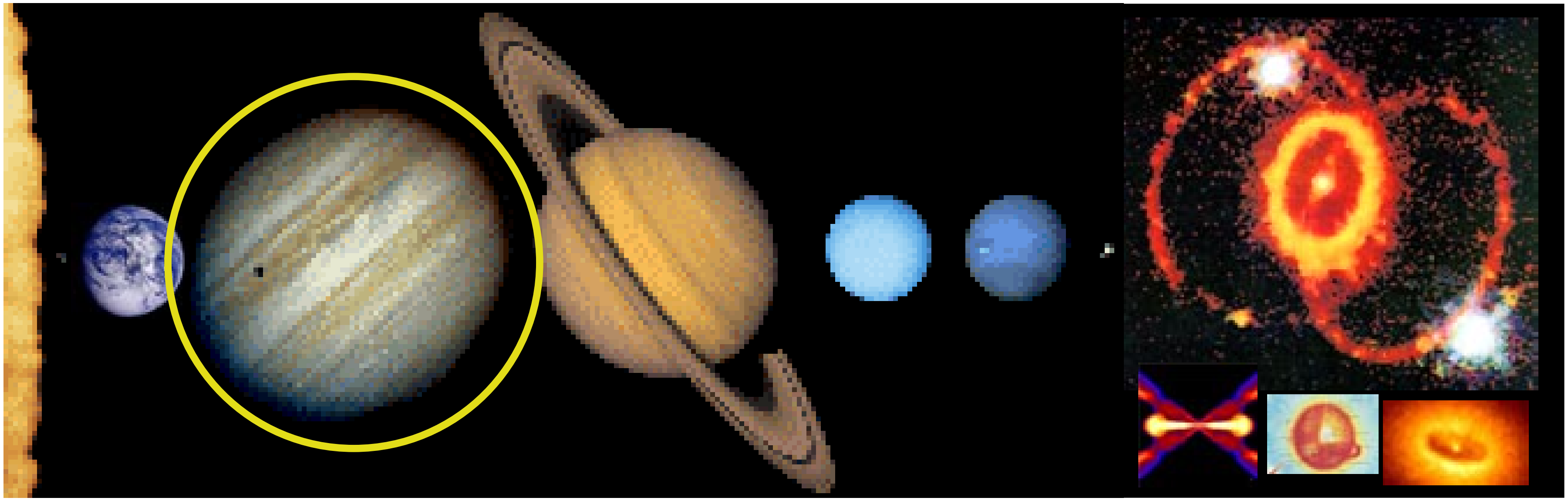


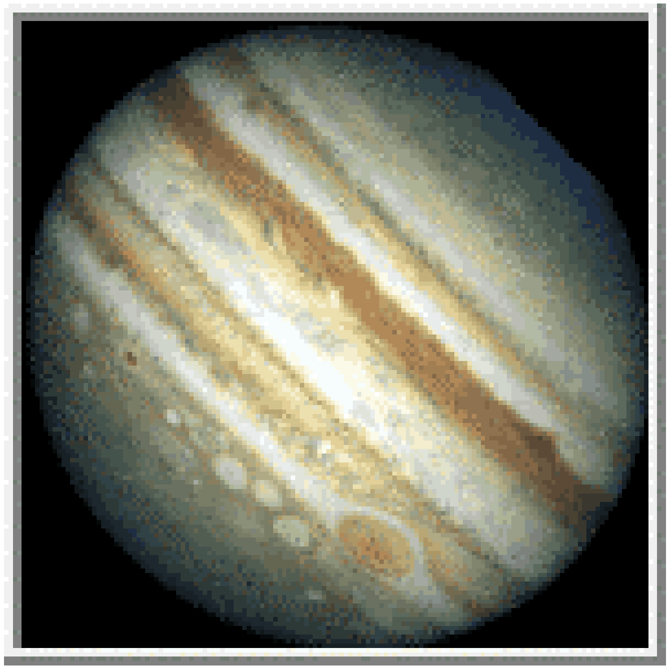
Outline

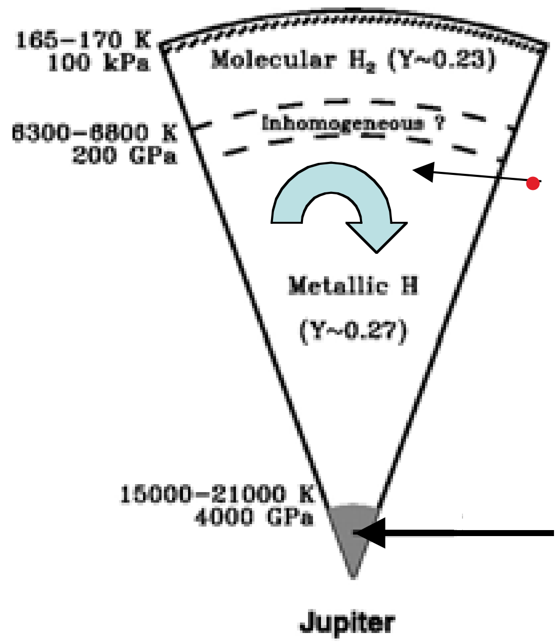


- **Significant advances in high energy density physics**
  - *Hugoniot equation-of-state*
  - *Materials science at high pressure*
  - *Hydrodynamics*
  - *Radiation transport and atomic physics*
- **Future directions**

EOS

Uncertainties in the equation-of-state of H and He have a large impact on models of the giant planets





1st order phase transition to metallic hydrogen? affects thermal evolution, He abundance, magnetic field

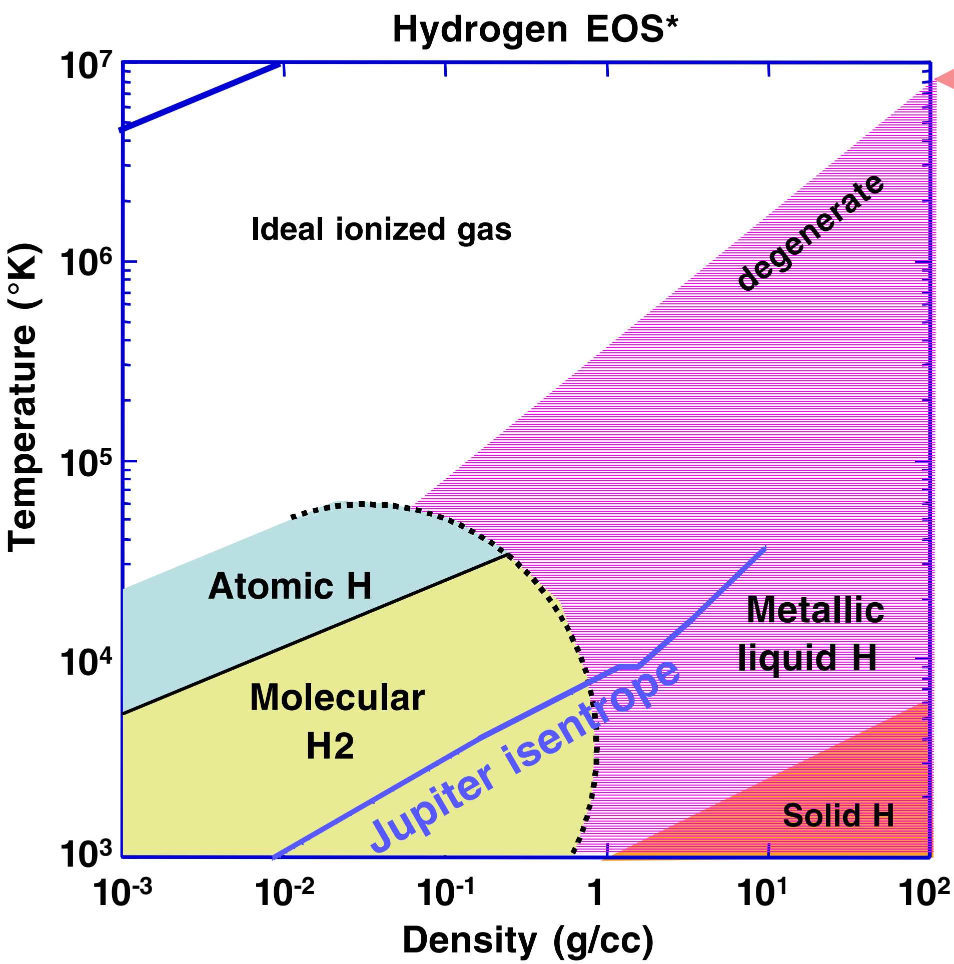
Core : solid or molten?

- **Models of Jupiter must match a limited set of measurements**
  - *Gravitational field (radius, mass)*
  - *Surface conditions (T, luminosity, spectra)*
- **Hydrogen EOS affects models**
  - *Density structure*
  - *Core*

Guillot, Science, 286, 72 (1999)

EOS

Accurate models of hydrogen EOS are difficult in these regimes



Degeneracy

- **kT ~ E (Fermi) =$p^2/2m_e$,**
- **Particle correlations become important**

VanHorn, Science,252(1991)

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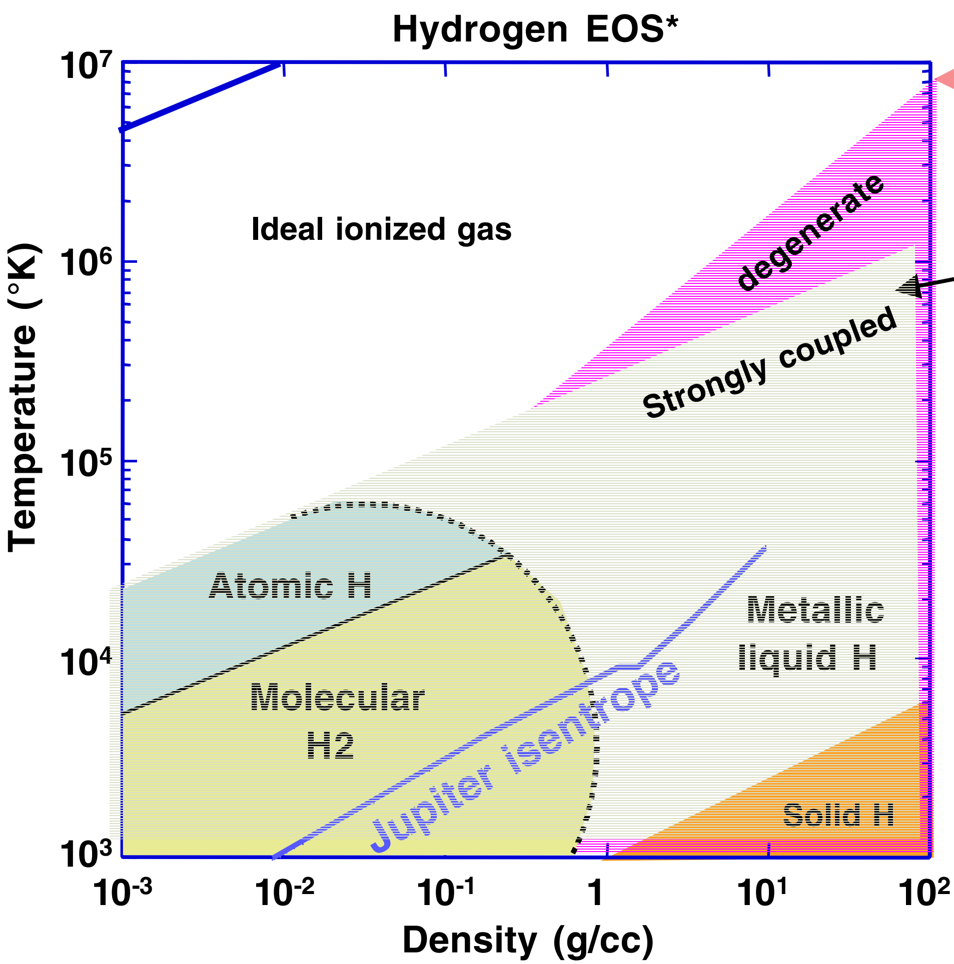

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Strongly coupled plasmas

$$\Gamma \equiv \frac{Z^2 e^2 / a}{kT} = \frac{Coulomb}{Thermal}$$

$$\propto Z^{5/6} n_e^{1/3} / T$$

- **Long range correlations become important**

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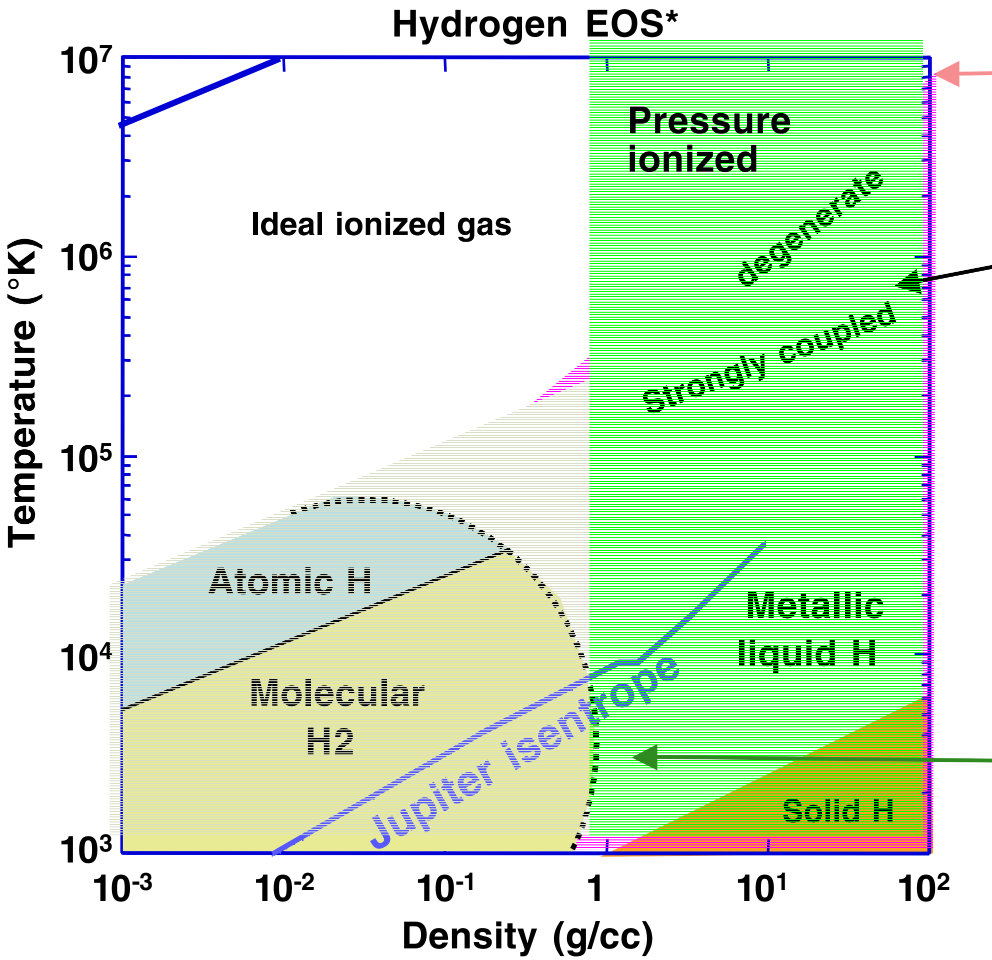

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- Bohr radius ~ inter-ion spacing
- Ionization potentials are depressed

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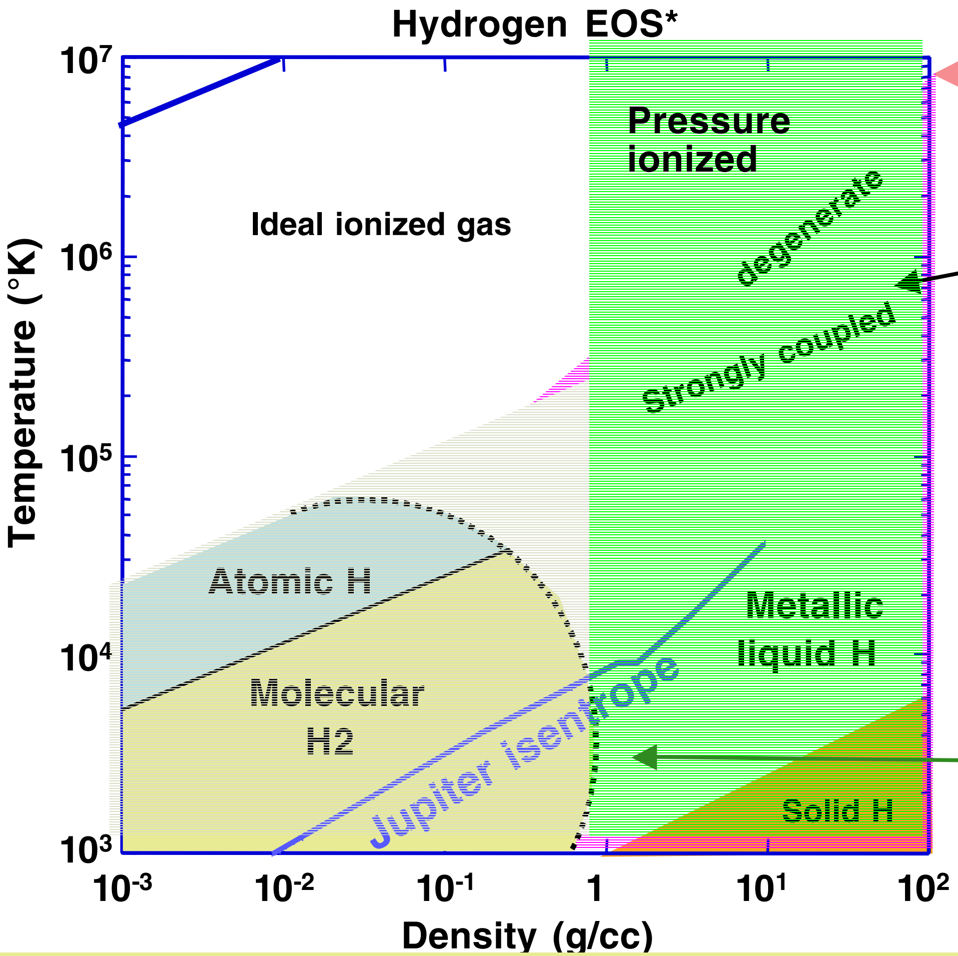

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Isentrope of Jupiter is strongly coupled and degenerate, and crosses the molecular and pressure ionized regimes

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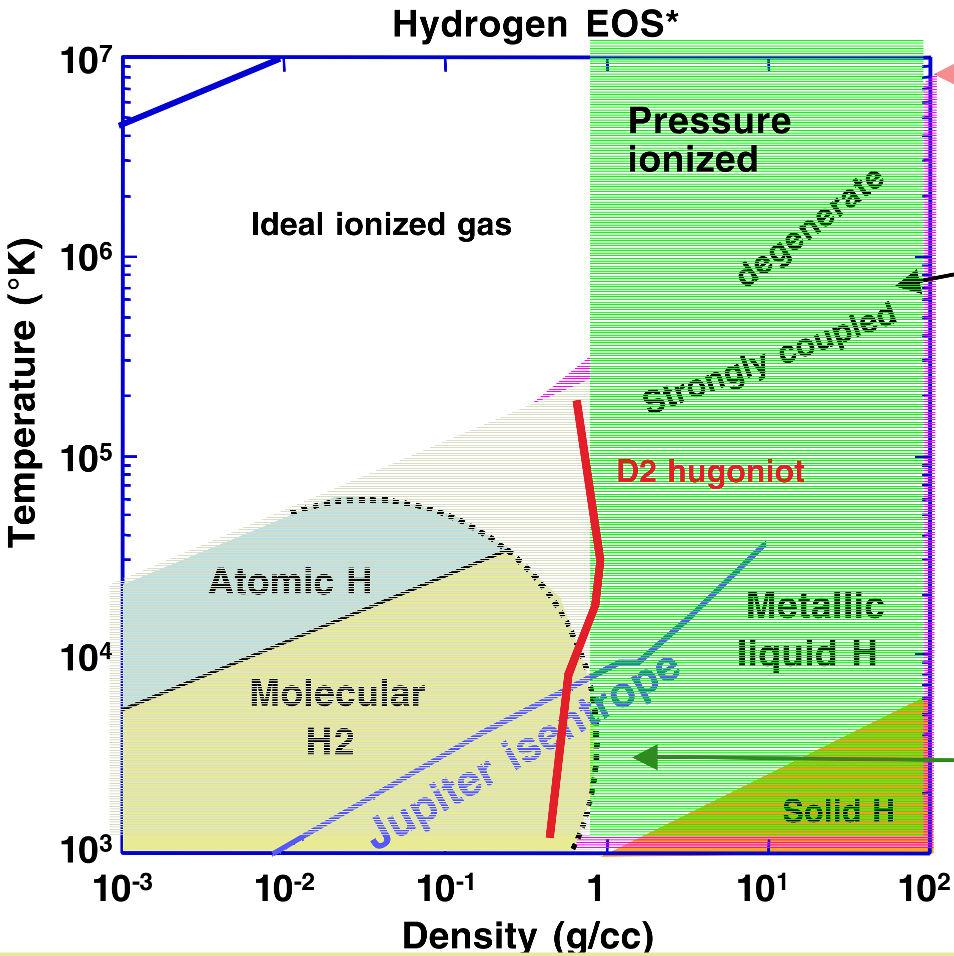

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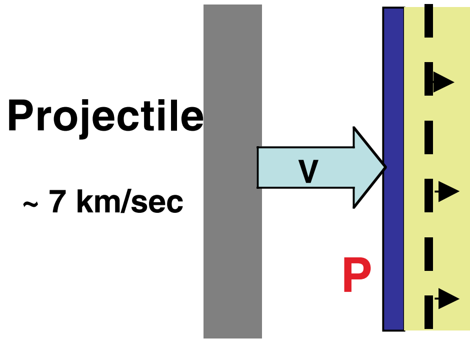
EOS data for extreme pressures are most accessible using shocks



P < .2 Mbars in D2

Nellis, J. Chem. Phys, 73 (1980)

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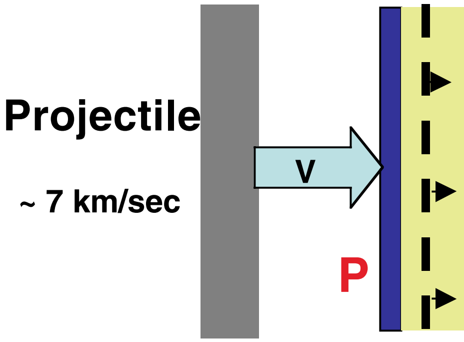

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Across a shock, conservation equations:

Mass: $\rho_0/\rho = 1 - u_p/U_S$

Momentum: $P - P_0 = \rho_0 U_S u_p$

Energy: $E - E_0 = .5 (P + P_0)(V_0 - V)$

Three equations in 5 unknowns

$\Rightarrow$ Velocity is easiest to measure

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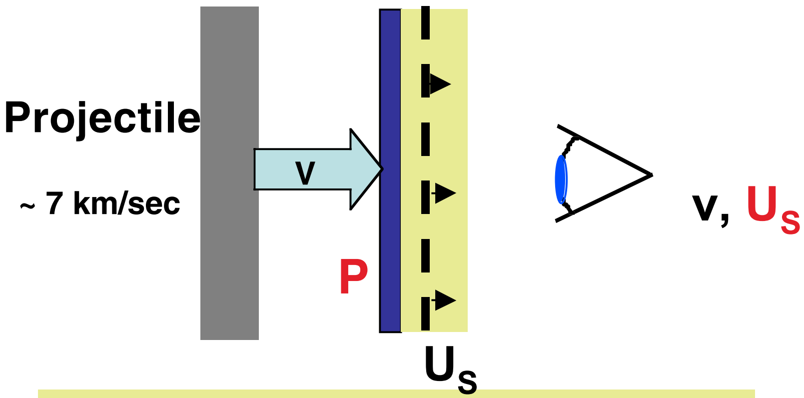

Impedance match
Need reference EOS v -> P

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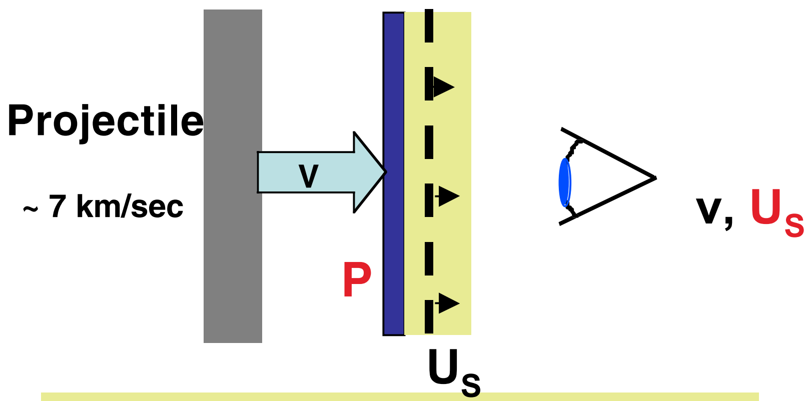

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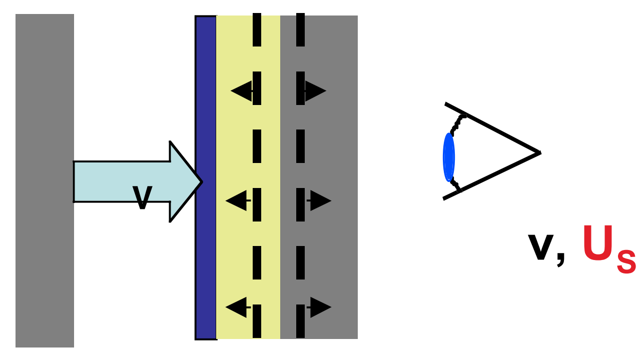

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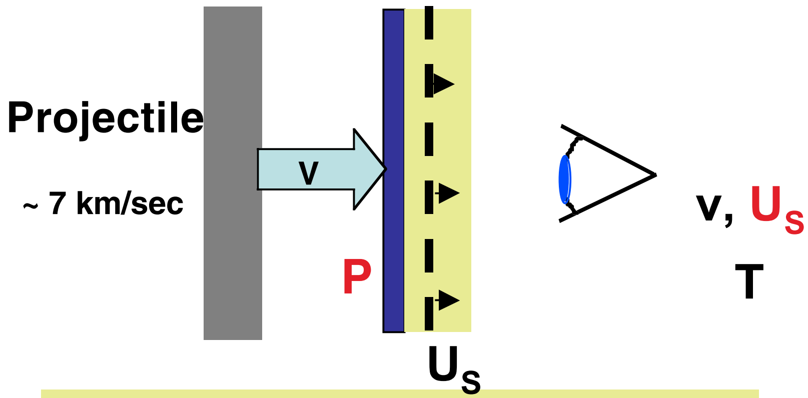

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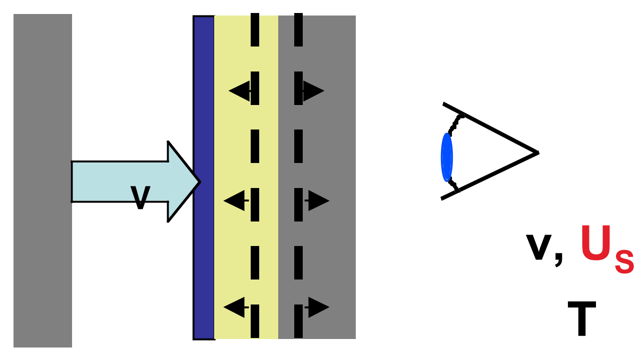
$\Rightarrow$ **Velocity is easiest to measure**

Measure temperature to get additional data for EOS models



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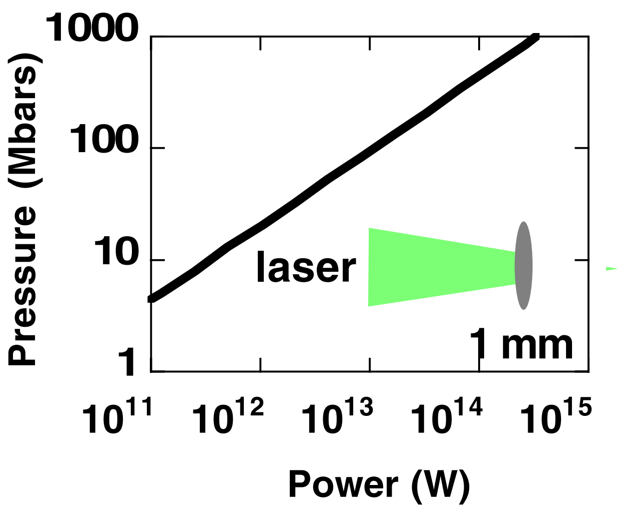
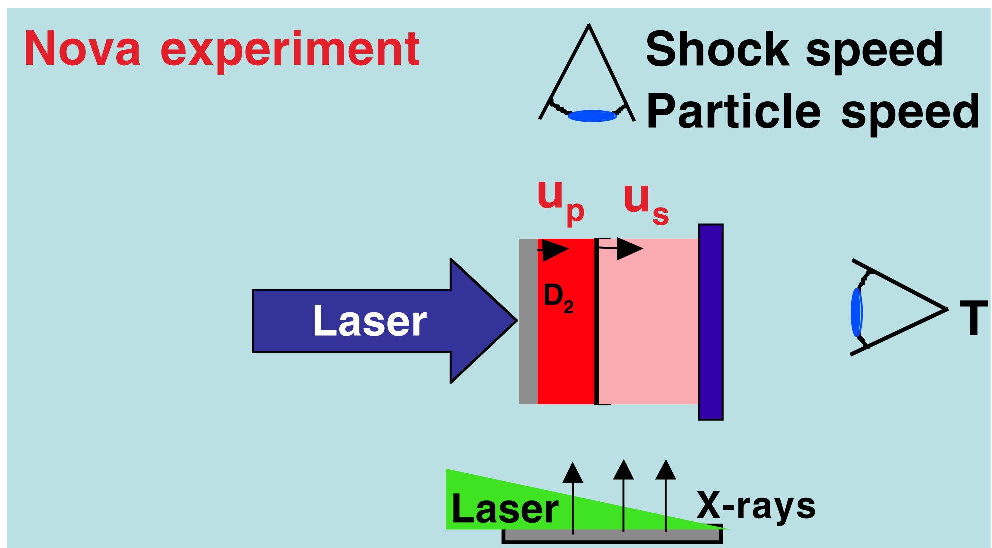
Nellis, J. Chem. Phys, 73 (1980)

Lasers generate high pressure shocks through ablation of material



- **Potential to get ultra high pressures P ~ I $^{2/3}$**
- **Potential to measure 2 quantities directly**
  - *Particle velocity u_p and shock velocity u_s*
  - *Absolute - no reference material EOS is required*
- **Making a precise measurement is difficult**

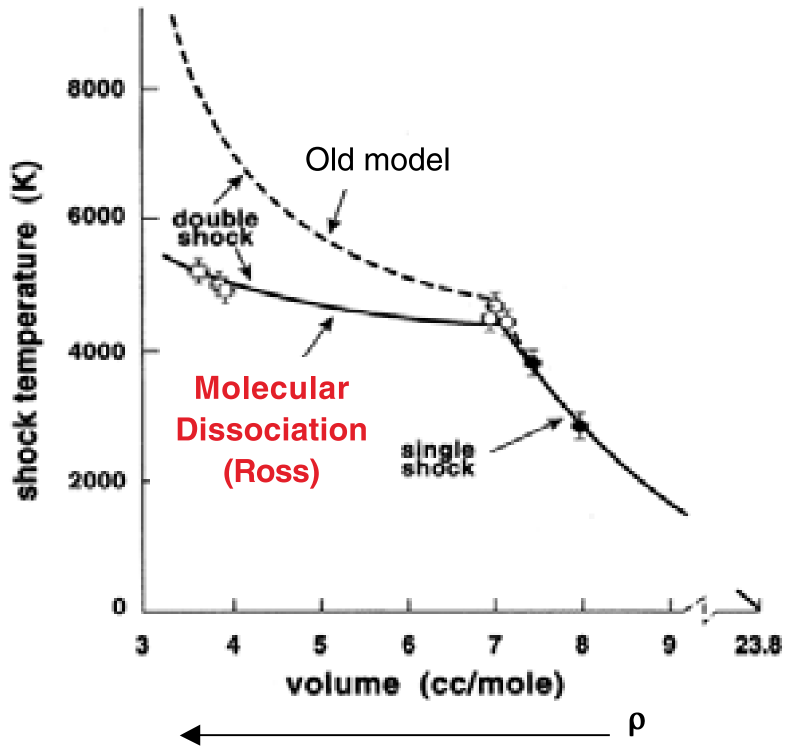


Da Silva, PRL, 78 (1997); Collins, PRL, 87 (2001)

EOS

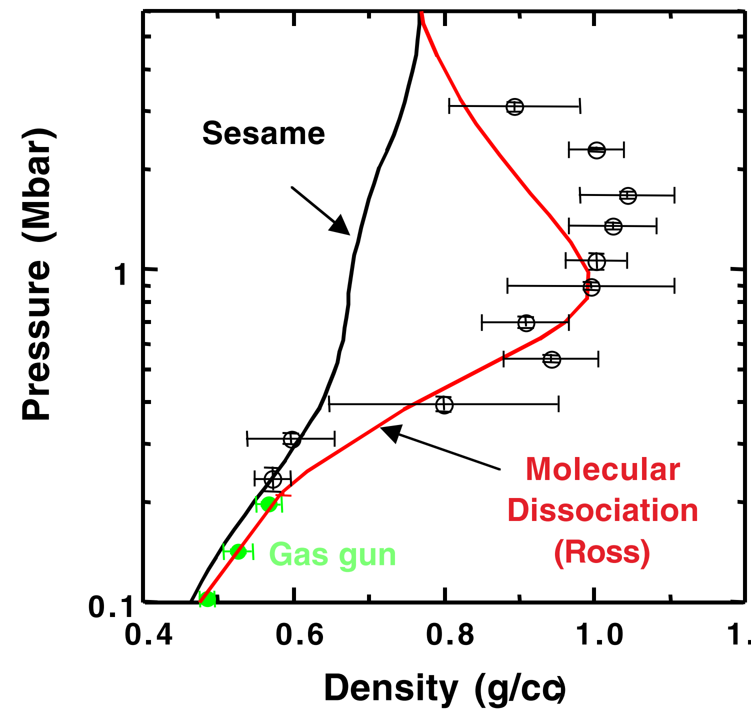
Shock temperature measurements in deuterium led to a model that predicted a softer EOS

New dissociation model required explain to gas gun data



Implies large compression on Hugoniot

Deuterium Hugoniot



Nova absolute shock Hugoniot data revealed 50% greater compressibility of hydrogen

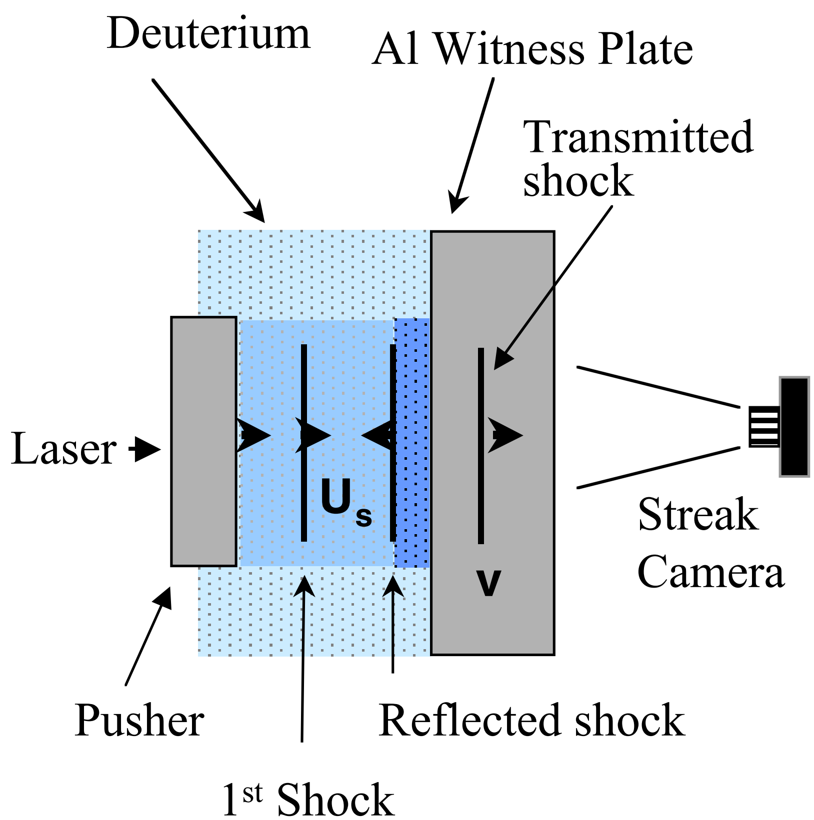
Holmes, PRB, 52(1995); Ross, J Chem Phys, 79 (1983)

Nellis, J. Chem Phys, 79 (1983); Da Silva, PRL, 78 (1997)

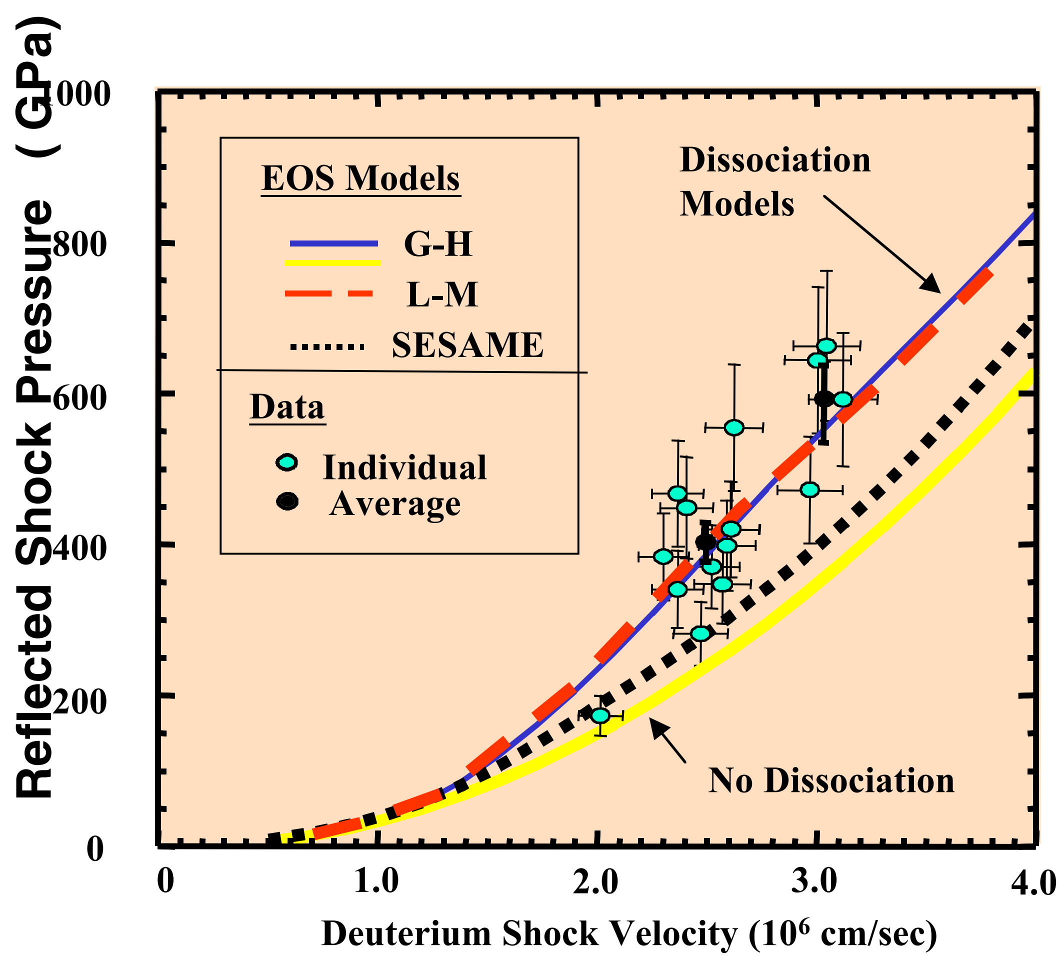
EOS

NRL Reflected Shock Experiments are Consistent with High Compressibility EOS Models

NRL



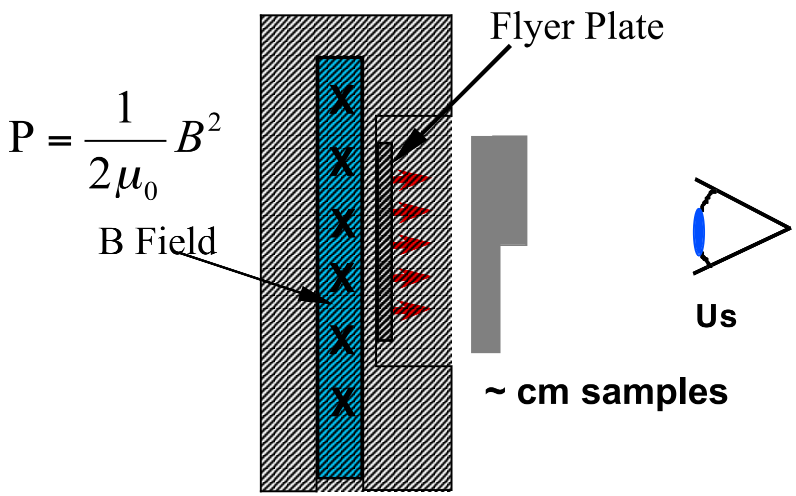
Measure U_s in D2
Measure v in Al -> P

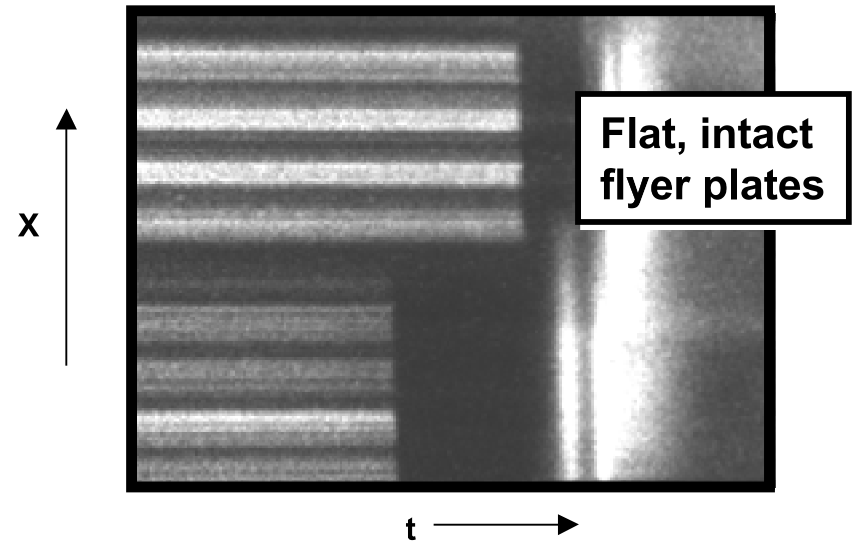


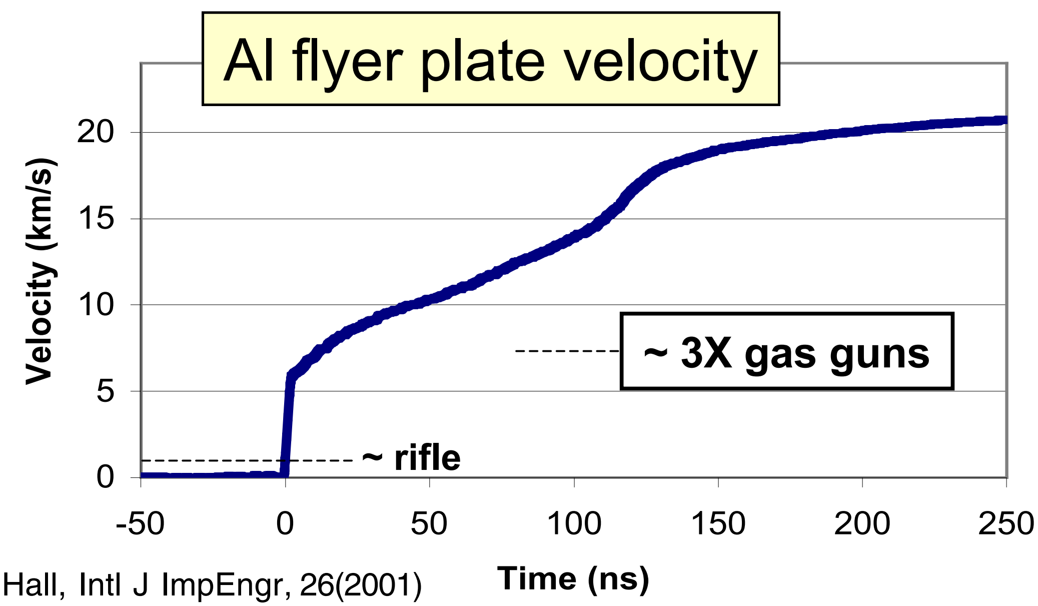
Mostovych, PRL, 85(2000); Mostovych, Phys Plas 8 (2001)

EOS

Magnetic driven ultra-high velocity flyer plates were developed for EOS measurements on Z







Hall, Intl J ImpEngr, 26(2001)

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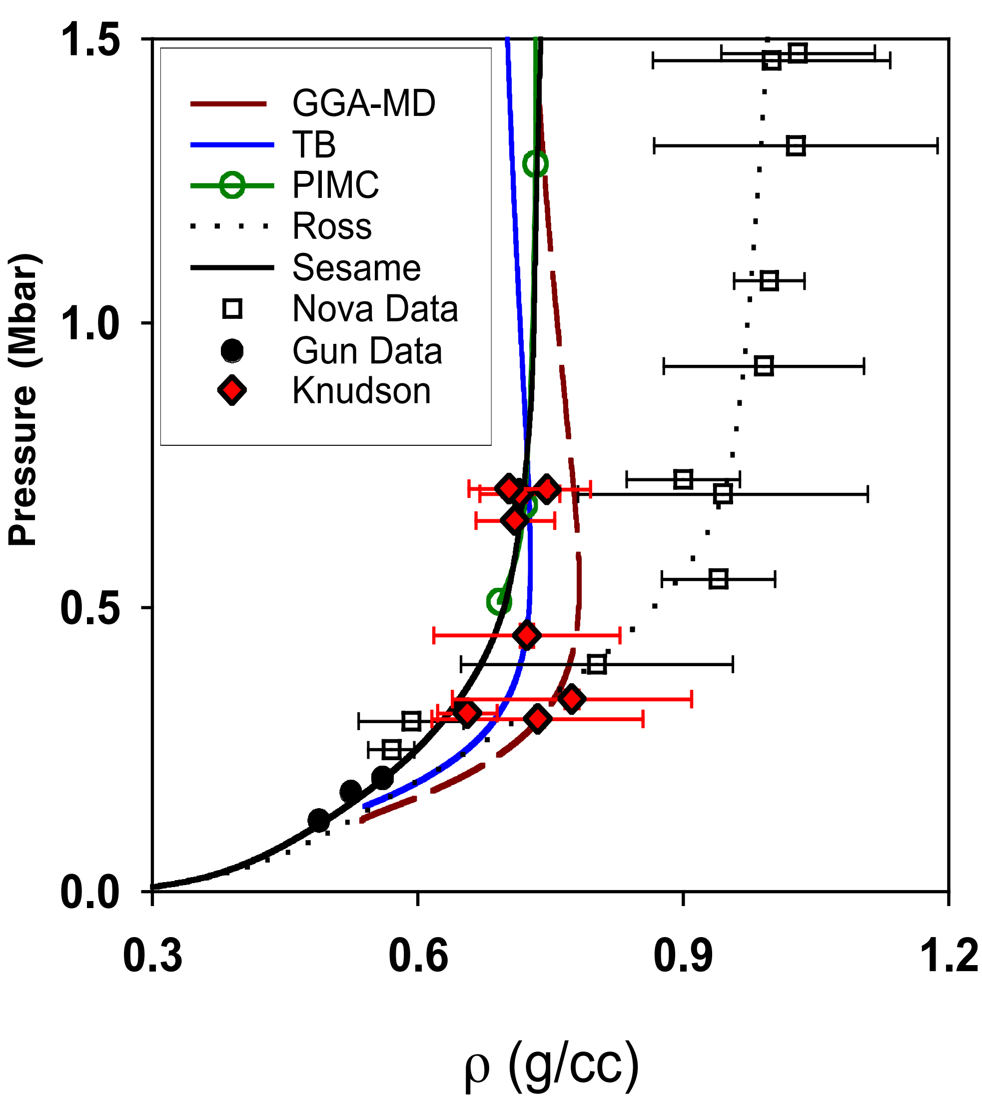
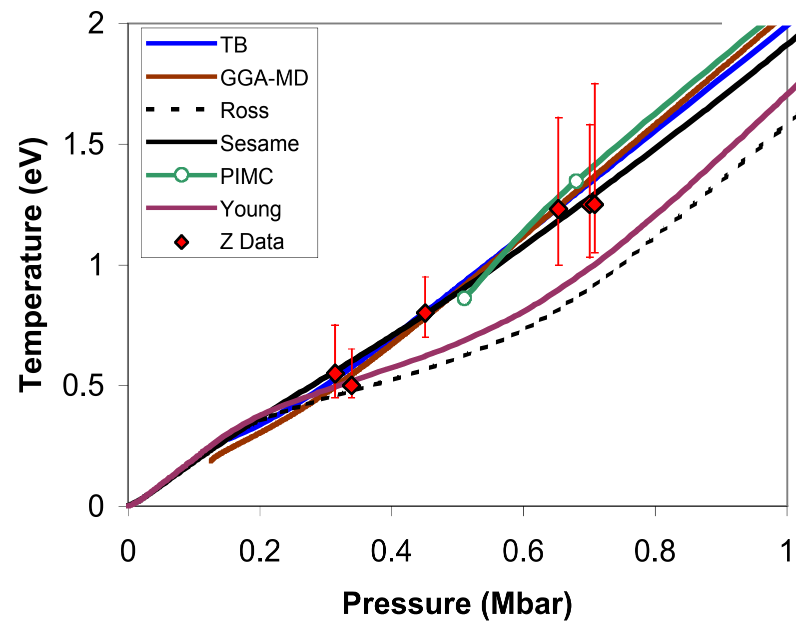
D_2 EOS data obtained on Z suggest a stiff response in agreement with Sesame and ab-initio models





Temperature measurements concured with Sesame

Knudson, PRL, 87, (2001)

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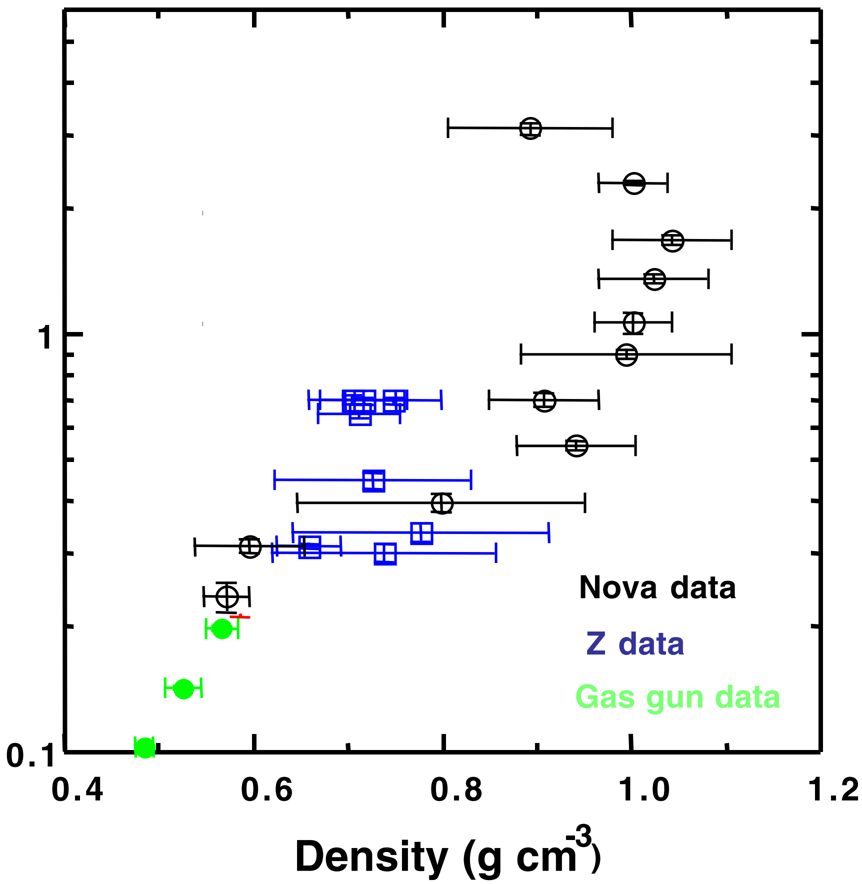
EOS

Models also have large differences in these regimes



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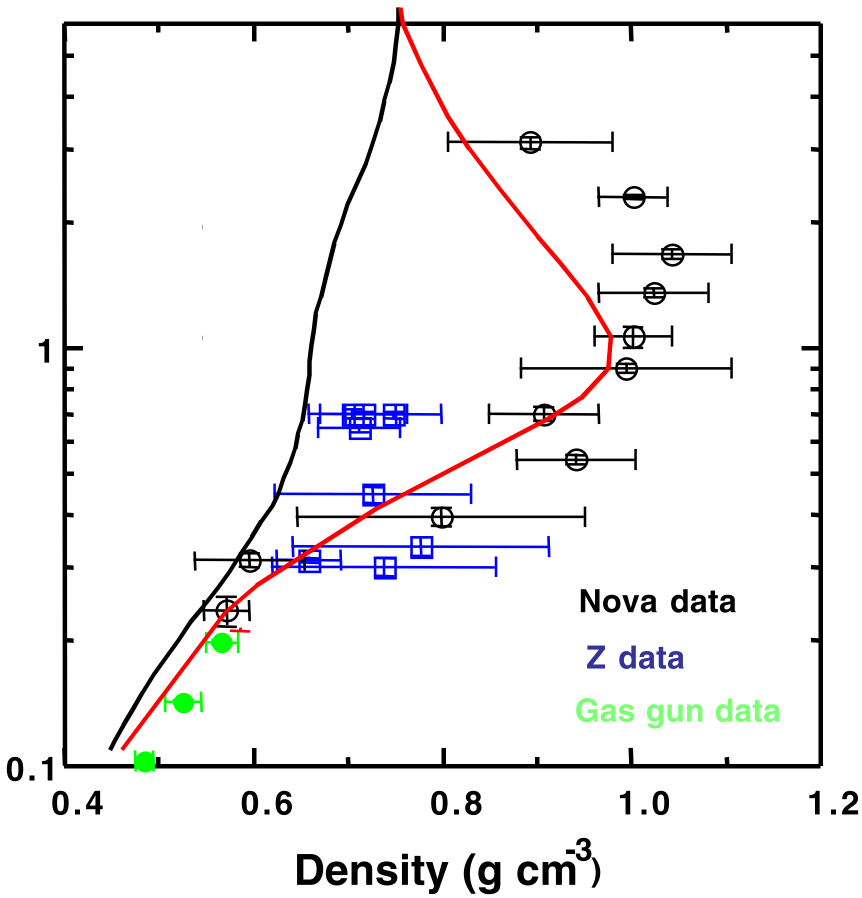

Statistical mechanics models

SESAME

Dissociation (Ross)

EOS

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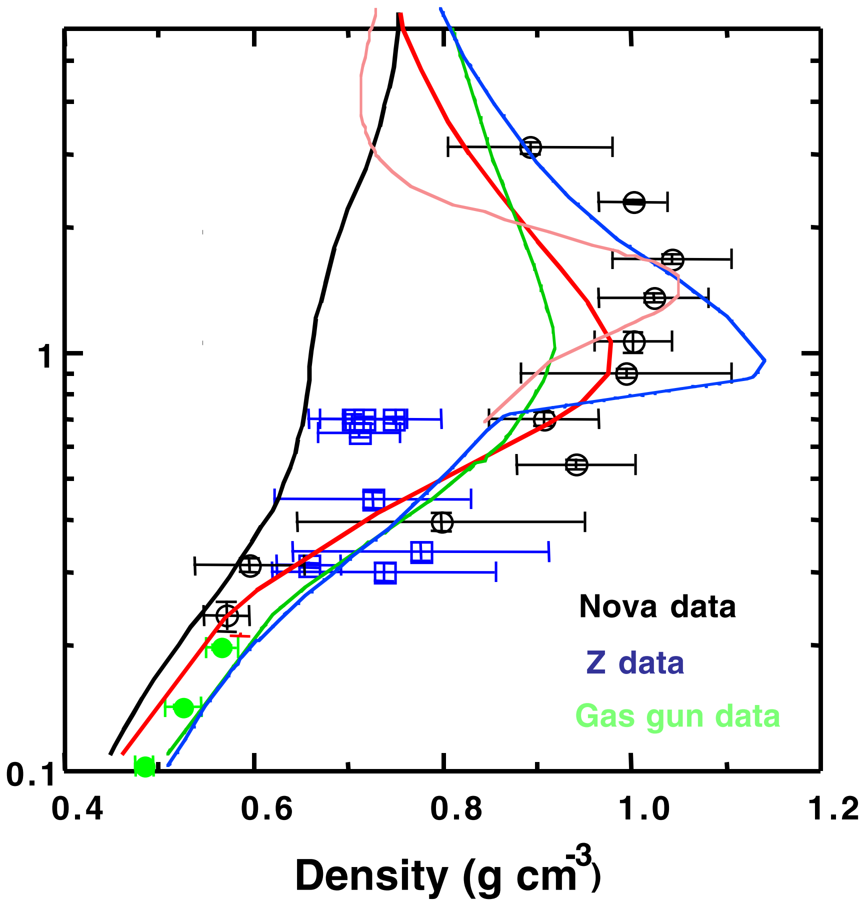

Statistical mechanics models

- SESAME
- Dissociation (Ross)
- Free energy: Redmer
- Free energy: Saumon-Chabrier
- Activity expansion: Rogers

EOS

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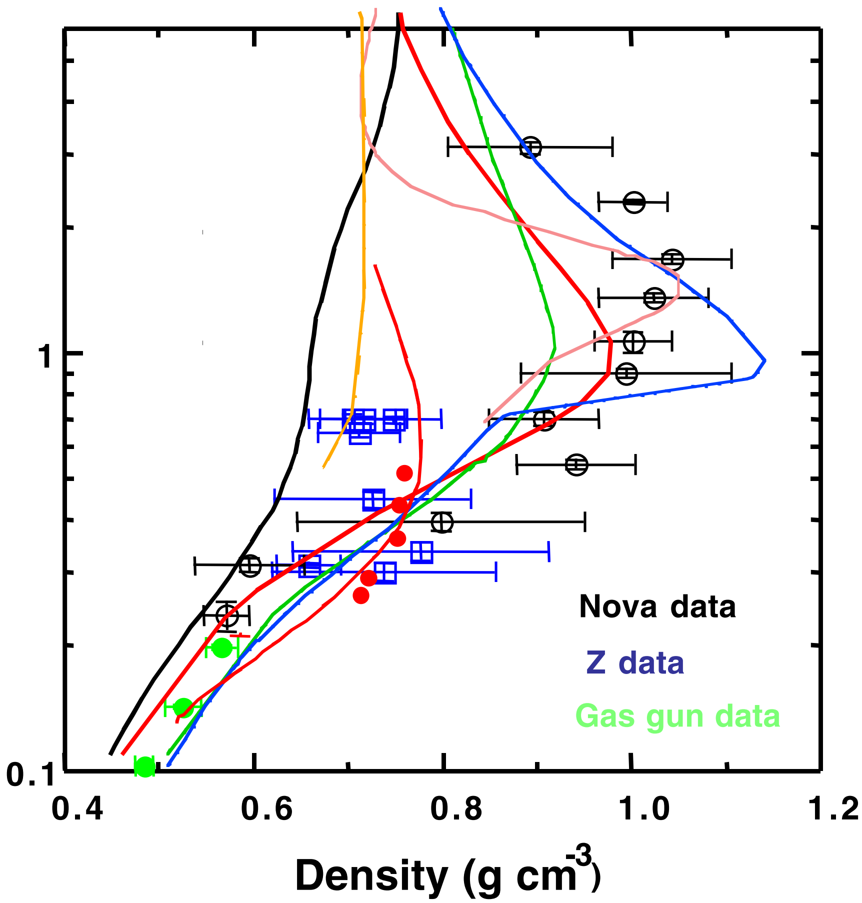

Statistical mechanics models

SESAME
Dissociation (Ross)
Free energy: Redmer
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Particle simulations

Path Integral MC: Militzer
Molecular dynamics: Lenosky
Molecular dynamics : Galli

EOS

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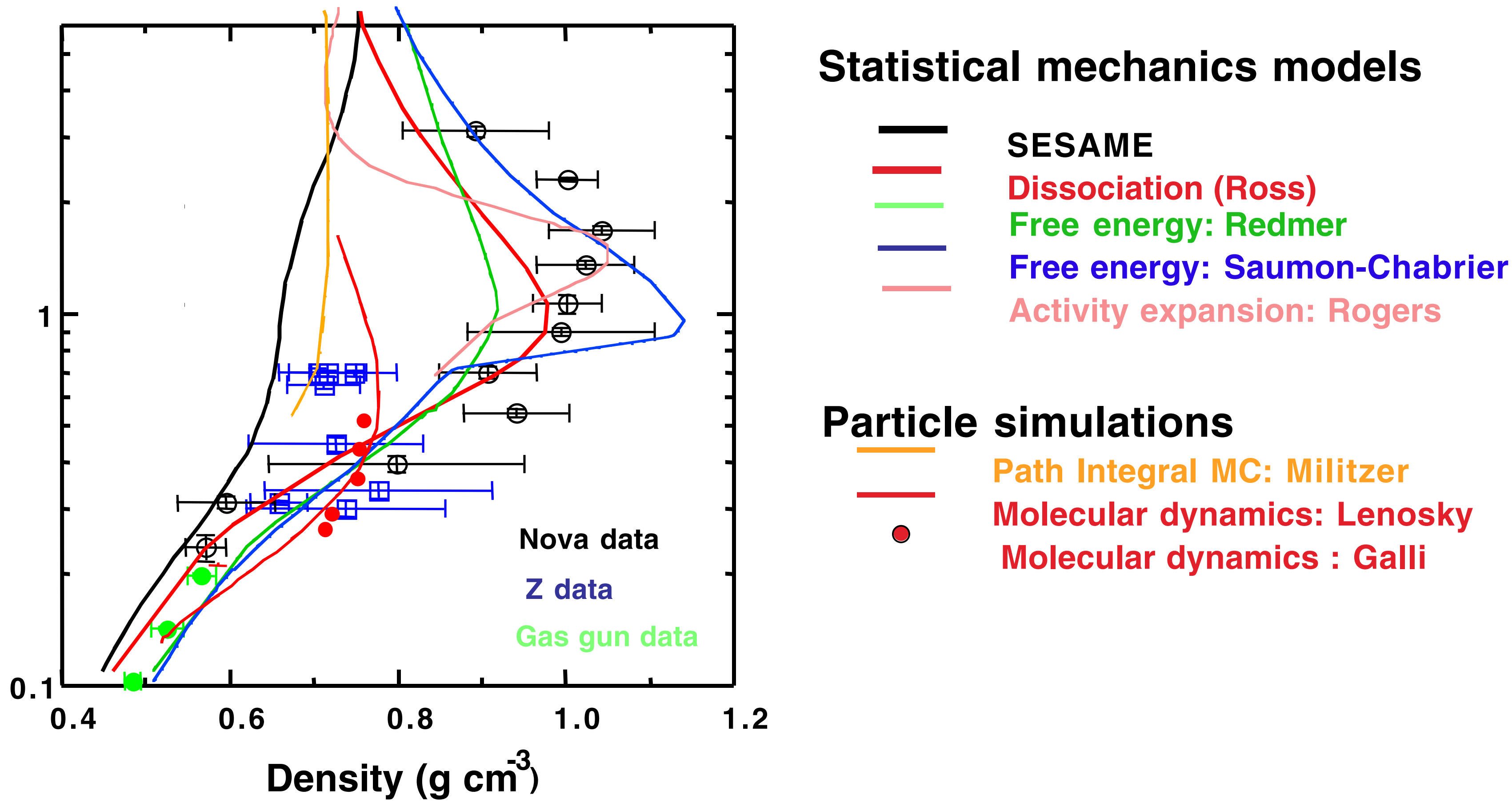

- **This is still very much work in progress: scientific method at work!**
  – *Stimulated large amount of theoretical work*

EOS

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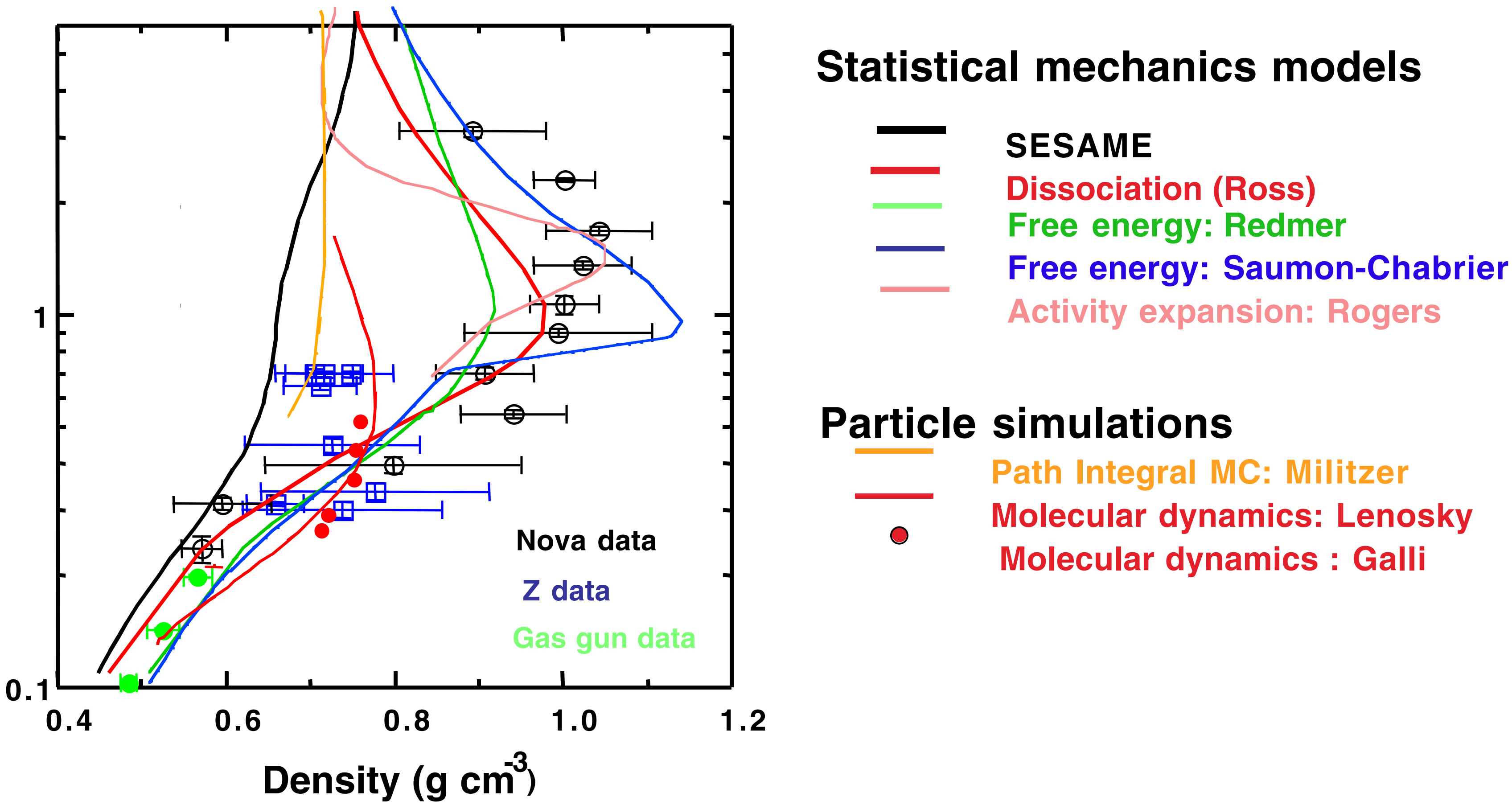
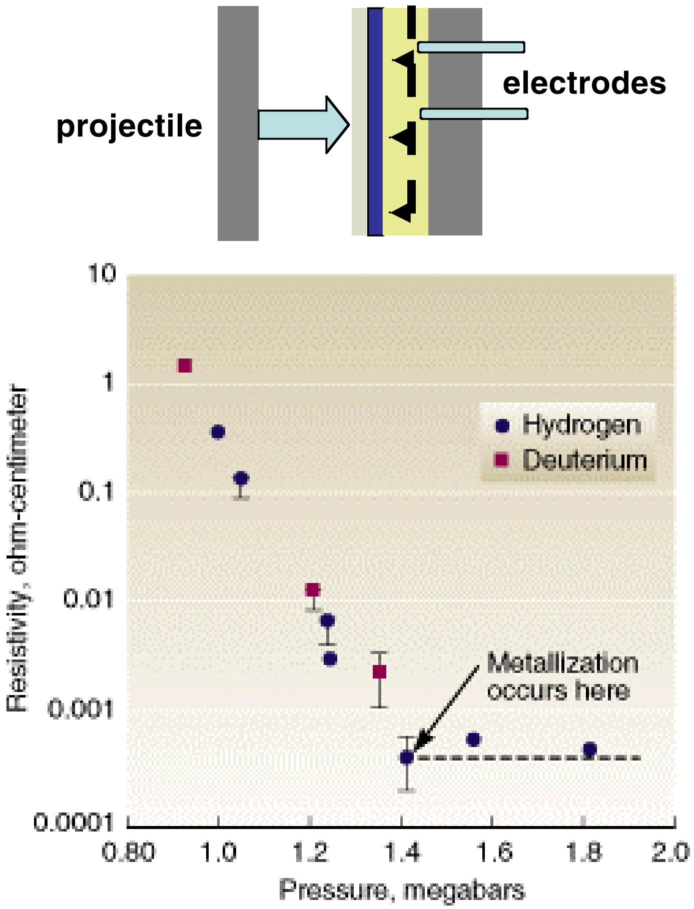
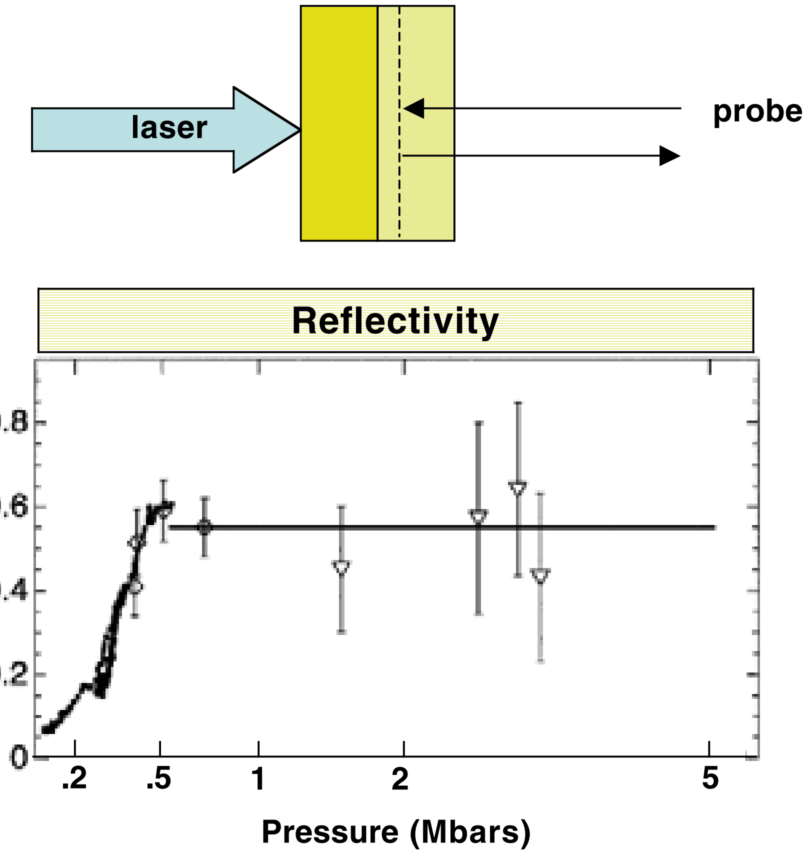


- **This is still very much work in progress: scientific method at work!**
  - *Stimulated large amount of theoretical work*
- **Only way to get high pressure Hugoniot EOS**

EOS

Measurements show a continuous transition from insulating to metallic state



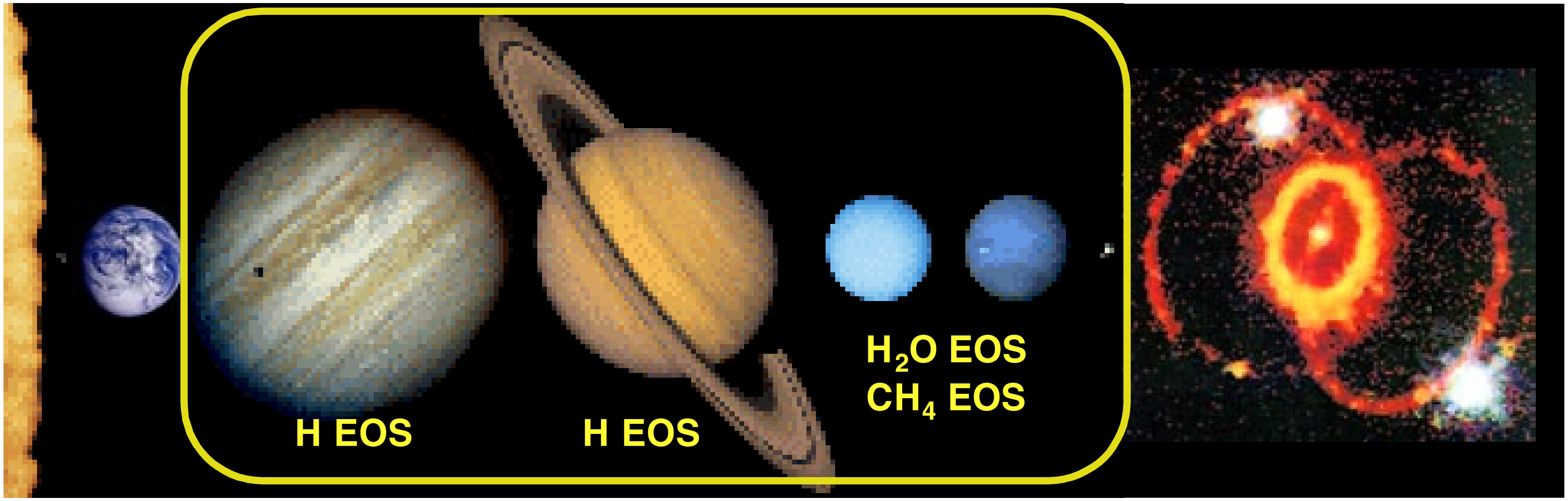


As shock pressure increases, D2 goes from transparent to a metallic reflector

- **Models of Jupiter and giant planets are being reevaluated**

Nellis, PRB 59(1999); Celliers, PRL 84 (2000)

Outline



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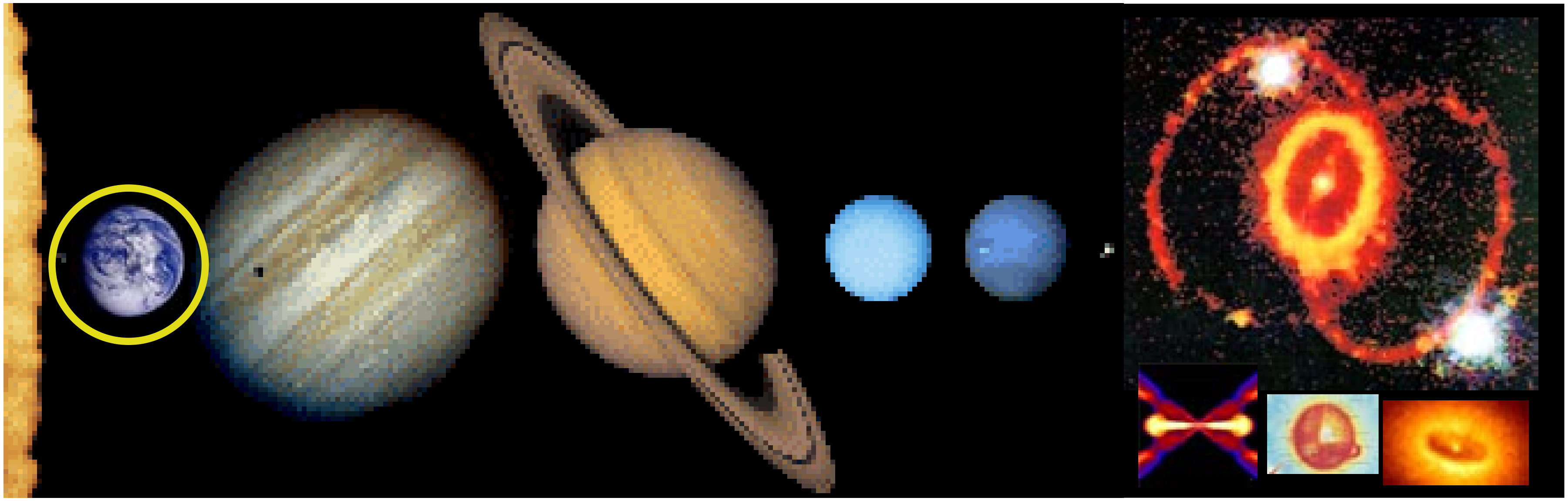

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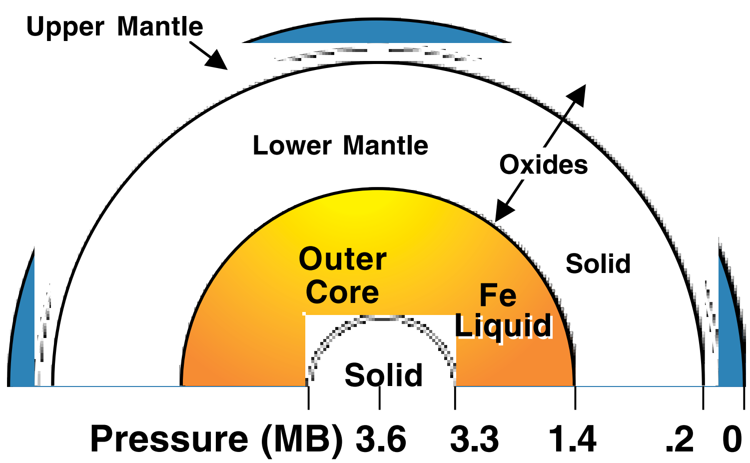
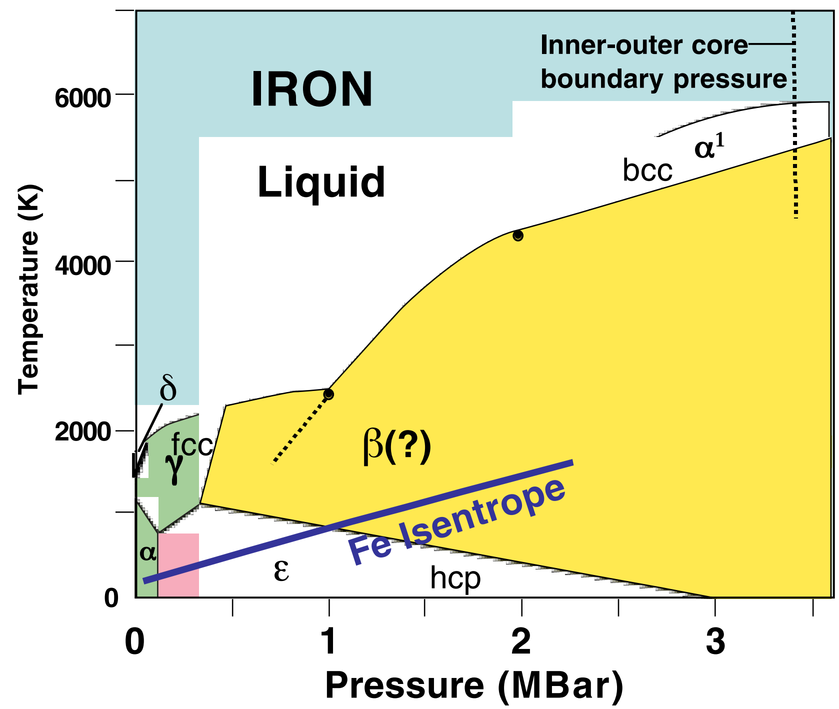
Material science

A new area of high energy density physics is the study of matter in the solid state under high pressure



- Earth's core contains solid Fe surrounded by liquid Fe
- Fe phase <-> earth's magnetic field

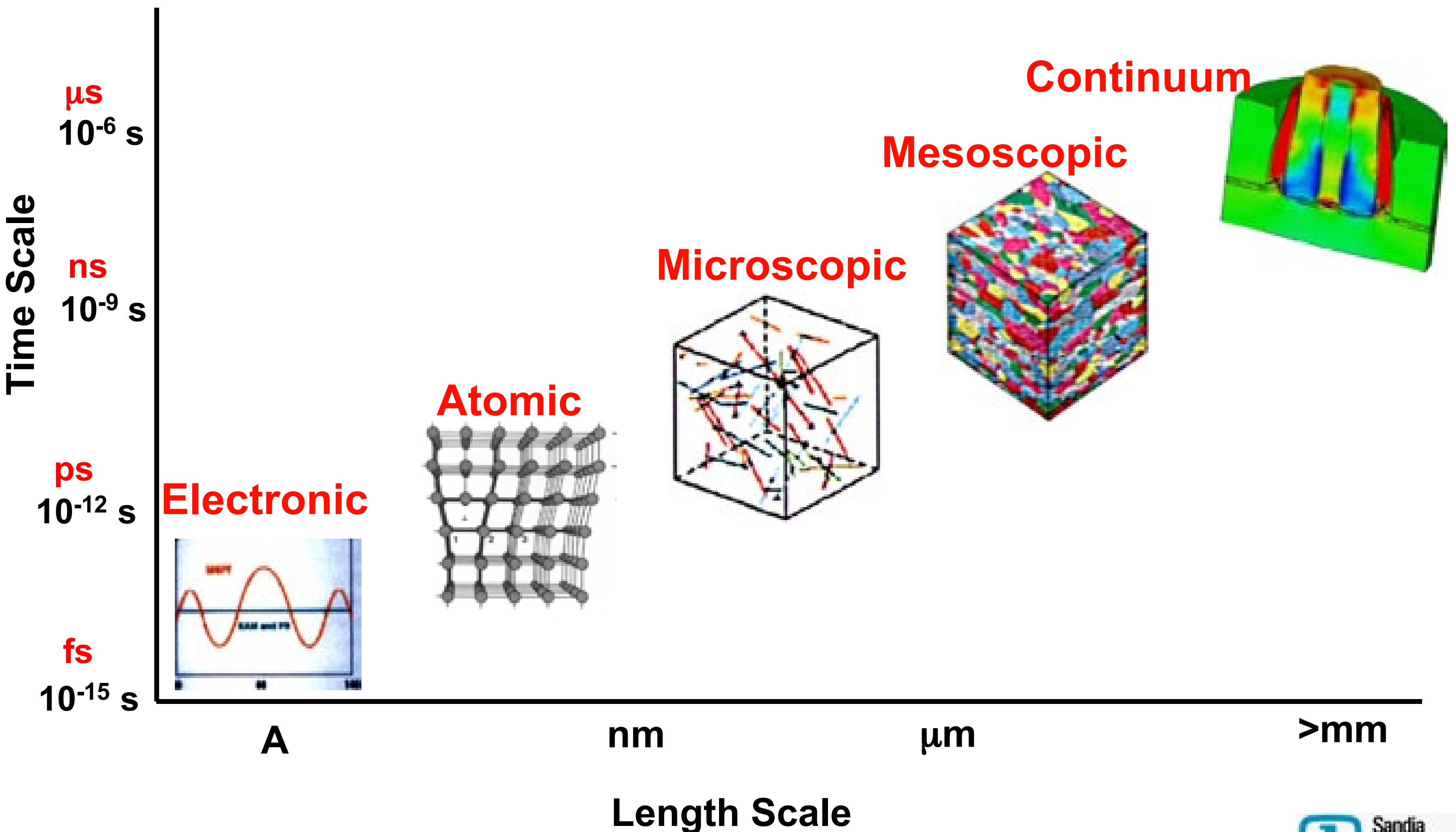


Anderson, O. L. Science **278** (1997)

- High-pressure phase boundaries and structure ?
- Mechanical properties at high pressure?

Compression along the isentropic can access high pressure solid states

Material response to compression in solids is complex and occurs on different scales



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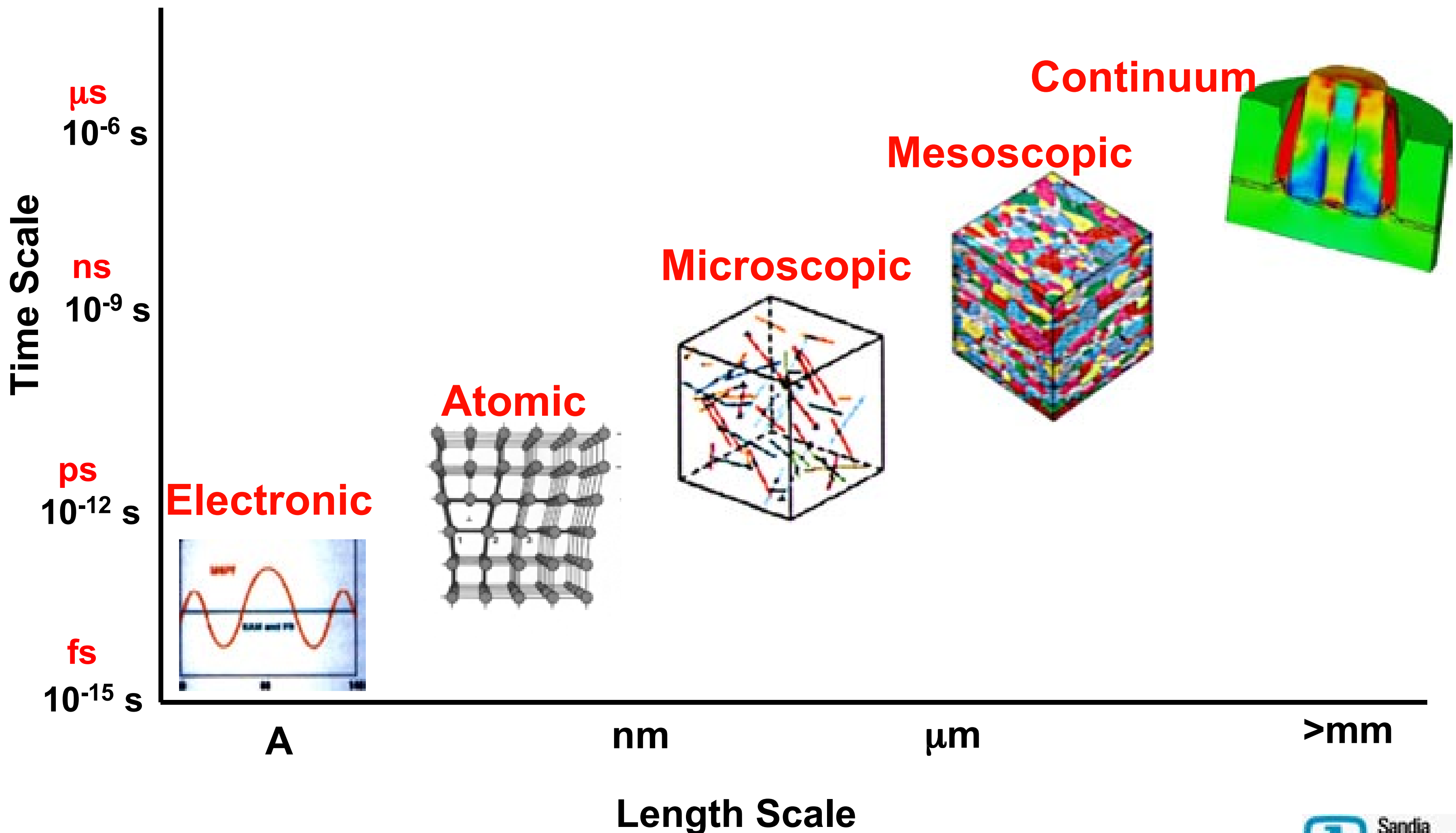

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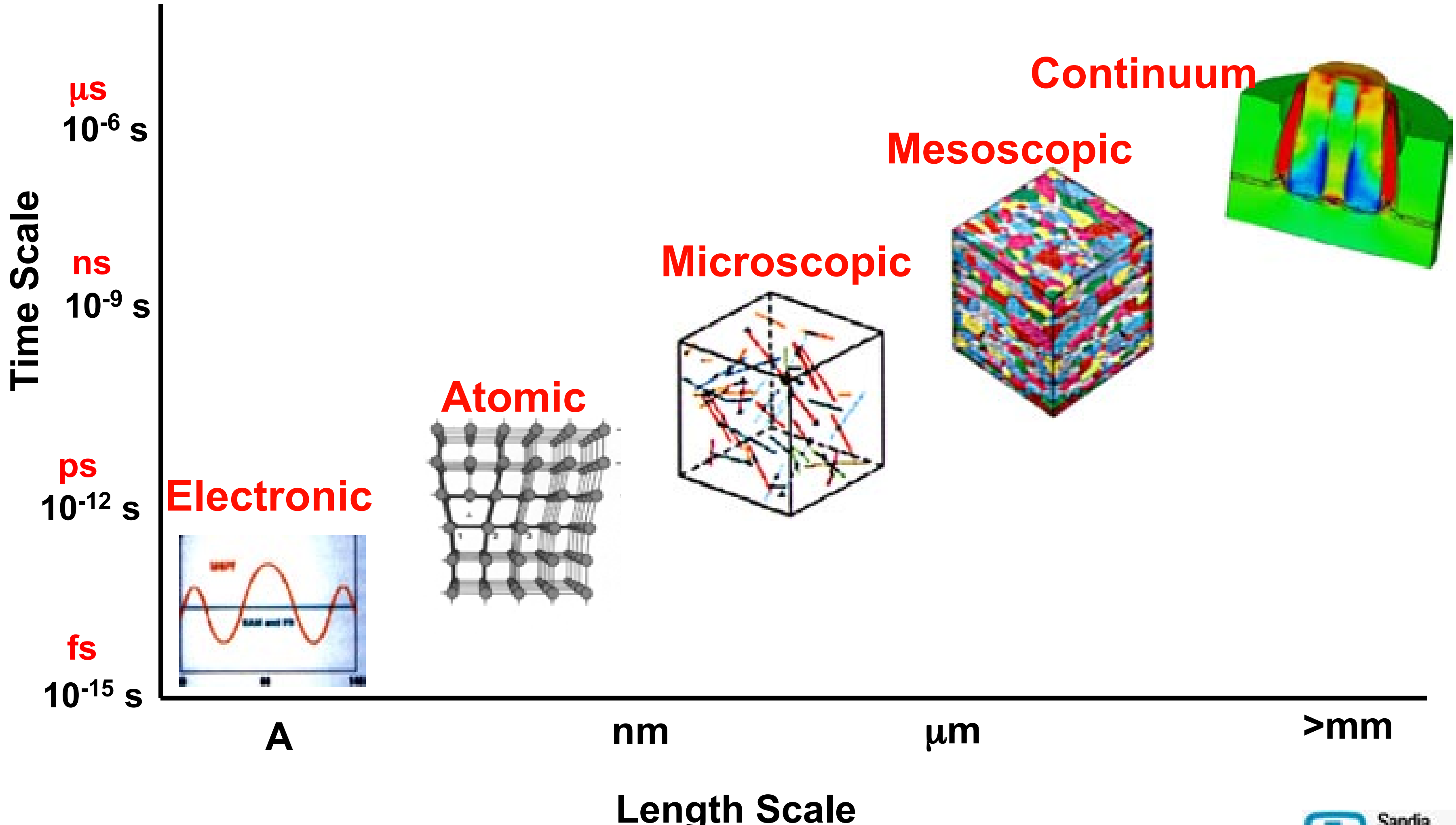

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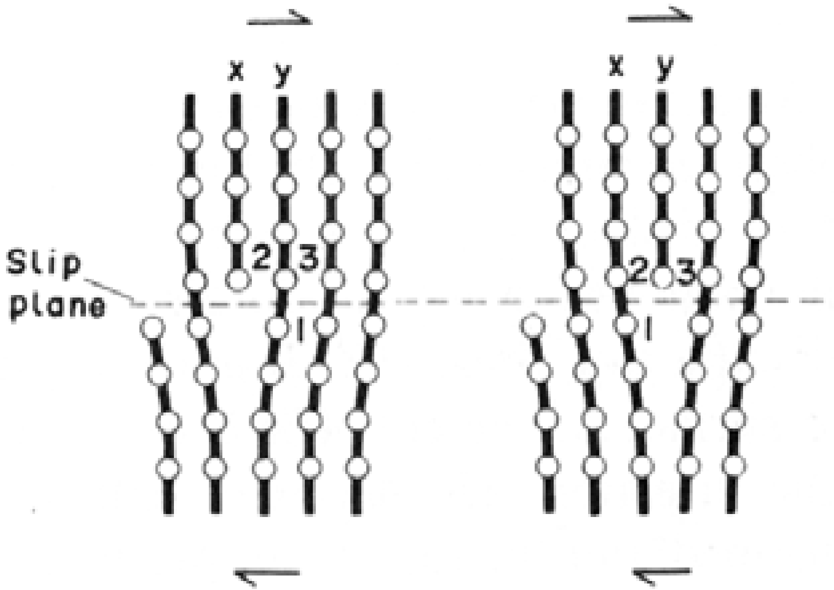
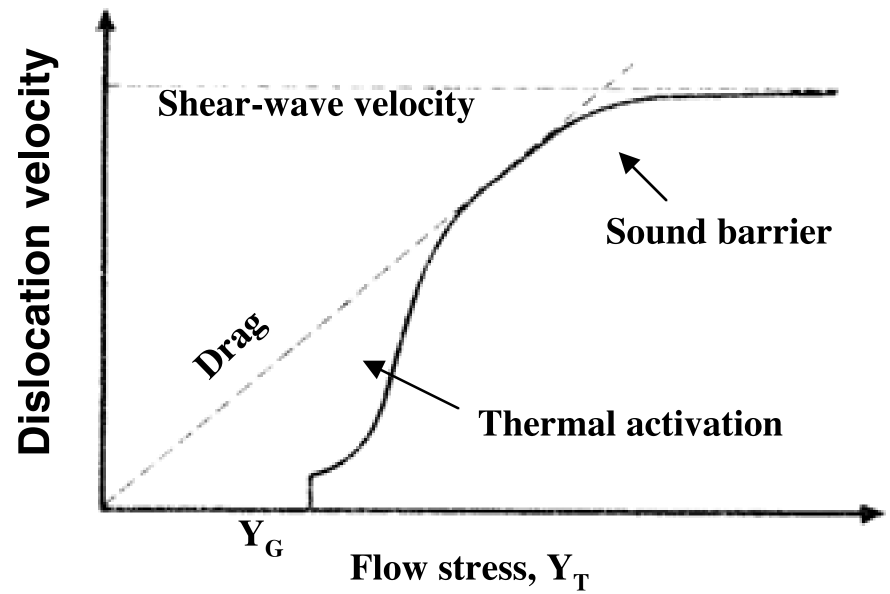
Strength is characterized by a material's resistance to dislocation transport

Shear stress



Shear stress



M.A. Meyers, Dynamic Behavior of Materials (Wiley, 1994), pp. 358-361

Deformation ~ strain rate ~ ave. disloc. vel.

$$\dot{\varepsilon} = \rho_m b \bar{v}_d$$

Dislocation density

Three categories of deformation are relevant :

1. **Thermally activated dislocation transport**
2. **Dislocation glide resisted by phonon drag**
3. **Dislocation "speed limit"**

The physics mechanisms underlying solid-state deformation can be categorized according to dislocation velocity or strain rate

We need data at high pressures and varying strain rates to compare with models of strength

Steinberg-Guinan constitutive model

Shear modulus

Work hardening

$$Y = Y_o f(\varepsilon) \frac{G(P,T)}{G_o}$$

P enhancement

T softening

$$G = G_o\left(1 + \left(\frac{G'_P}{G_o}\right)\frac{P}{\eta^{1/3}} - \cancel{\left(\frac{G'_T}{G_o}\right)(T - 300)}\right)$$

- SG semiempirical model with data at low pressures and strain rates
- Strain rate independent

Steinberg, JAP, 51 (1980)

Soderlind & Moriarty, Phys. Rev. B 57, 10340 (1998)

Mechanical properties

We need data at high pressures and varying strain rates to compare with models of strength

Steinberg-Guinan constitutive model

Shear modulus

Work hardening

$$Y = Y_o f(\varepsilon) \frac{G(P,T)}{G_o}$$

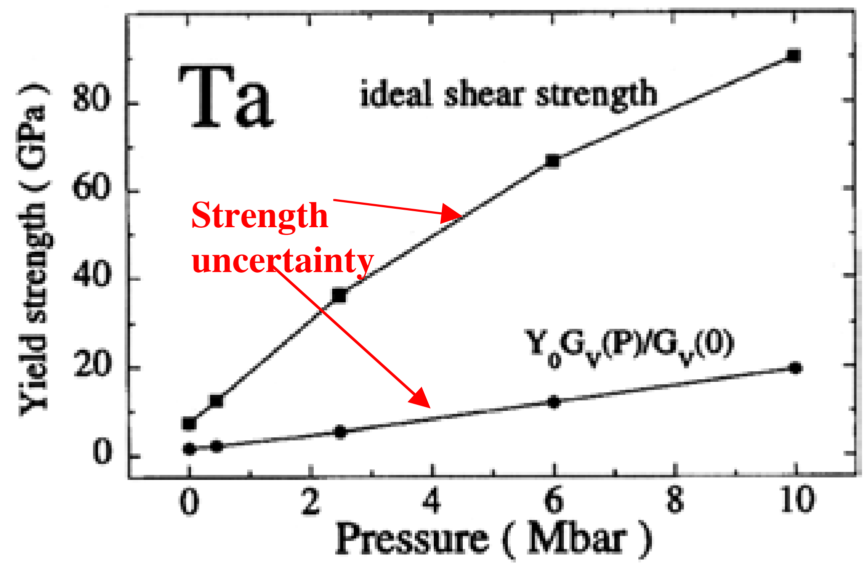
P enhancement

T softening

$$G = G_o \left(1 + \left(\frac{G'_P}{G_o} \right) \frac{P}{\eta^{1/3}} - \cancel{\left(\frac{G'_T}{G_o} \right) (T - 300)} \right)$$

- SG semiempirical model with data at low pressures and strain rates
- Strain rate independent

Ab-initio calculations



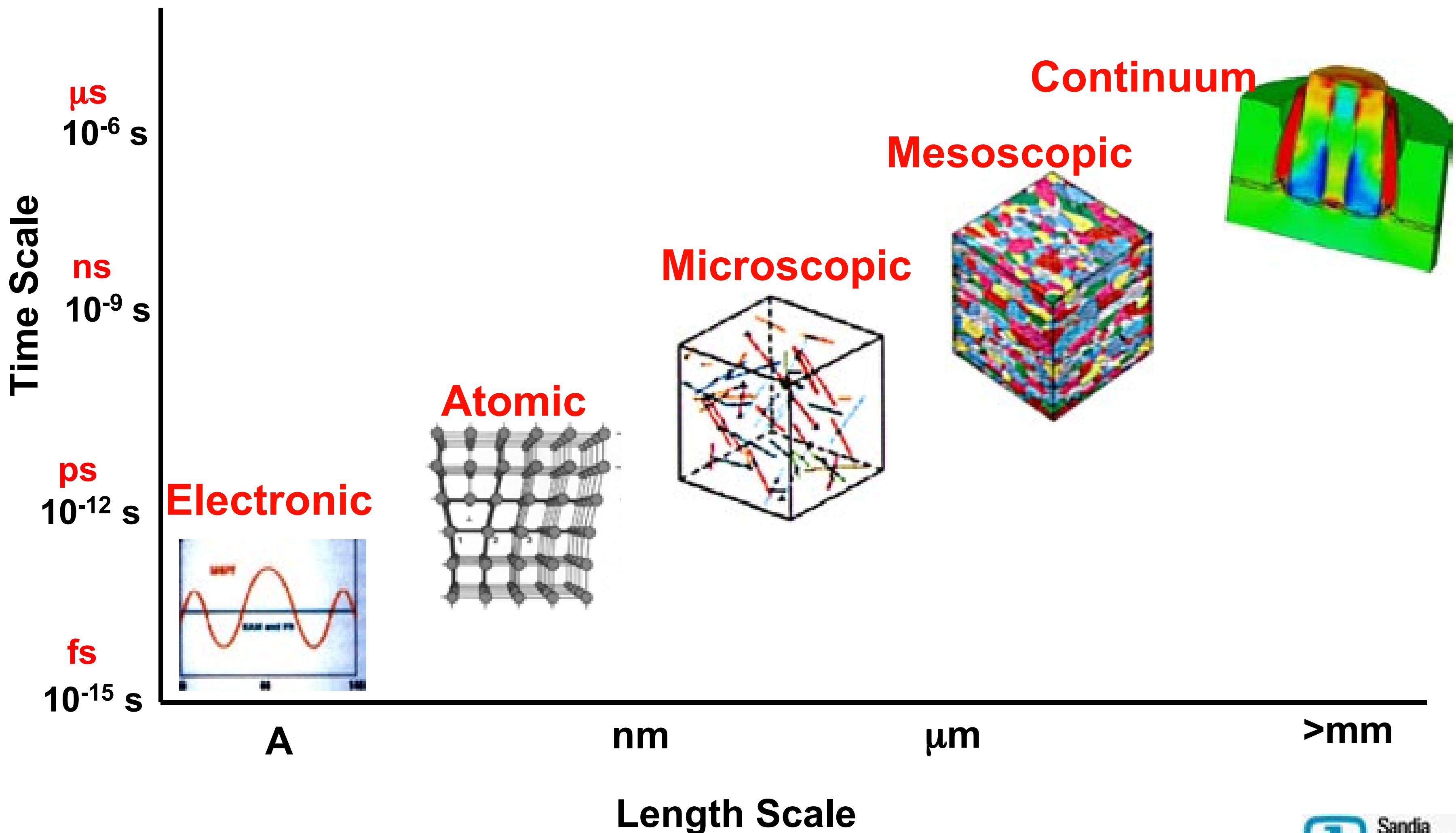
•At high pressure, there is an 4x difference in predictions of the strength

Steinberg, JAP, 51 (1980)

Soderlind & Moriarty, Phys. Rev. B 57, 10340 (1998)

Material science

Understanding mechanical properties requires measurements at each length scale

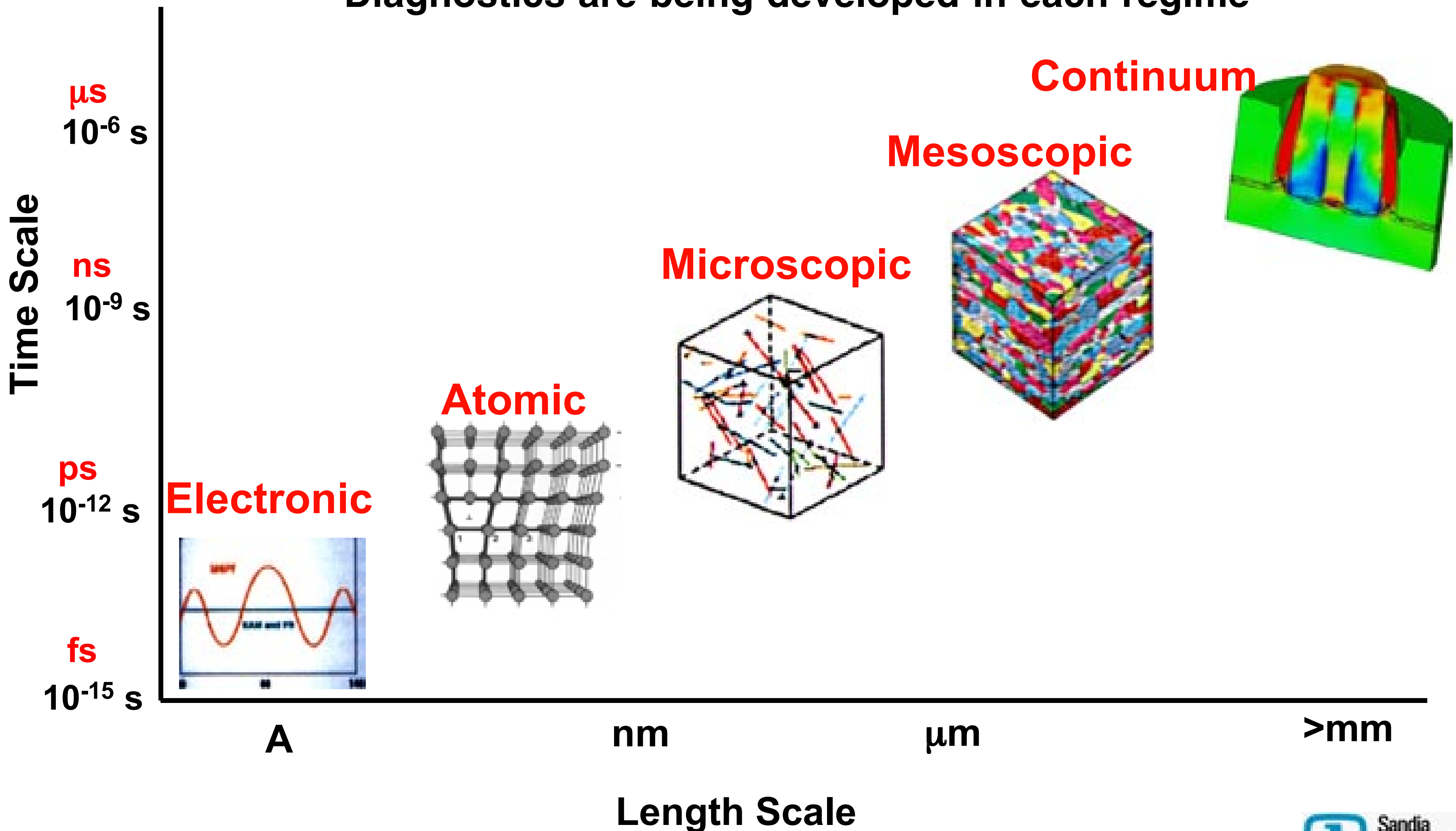


Sandia National Laboratories

Material science

Understanding mechanical properties requires measurements at each length scale

Diagnostics are being developed in each regime



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Material science

Understanding mechanical properties requires measurements at each length scale

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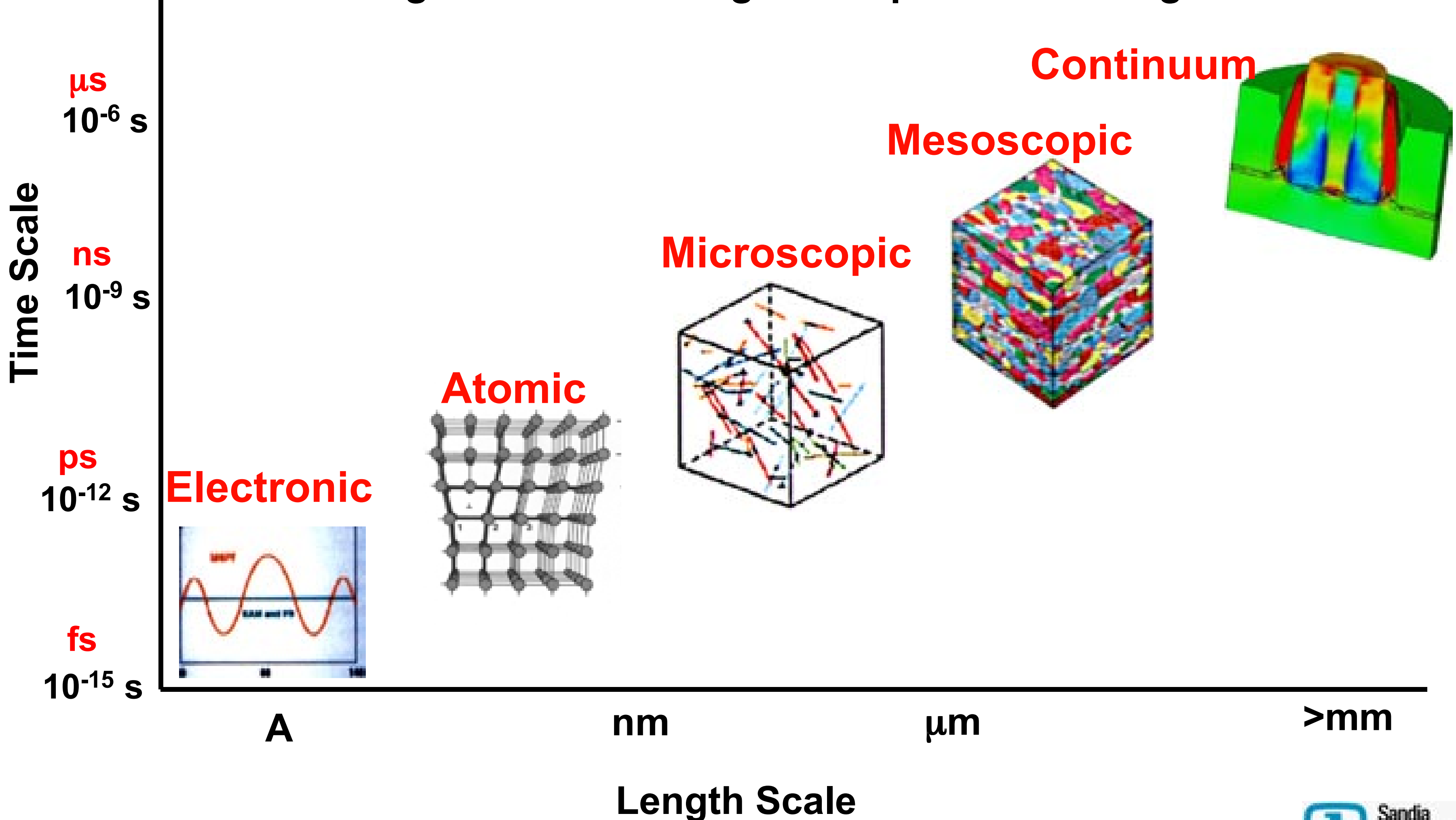

Sandia National Laboratories

Material science

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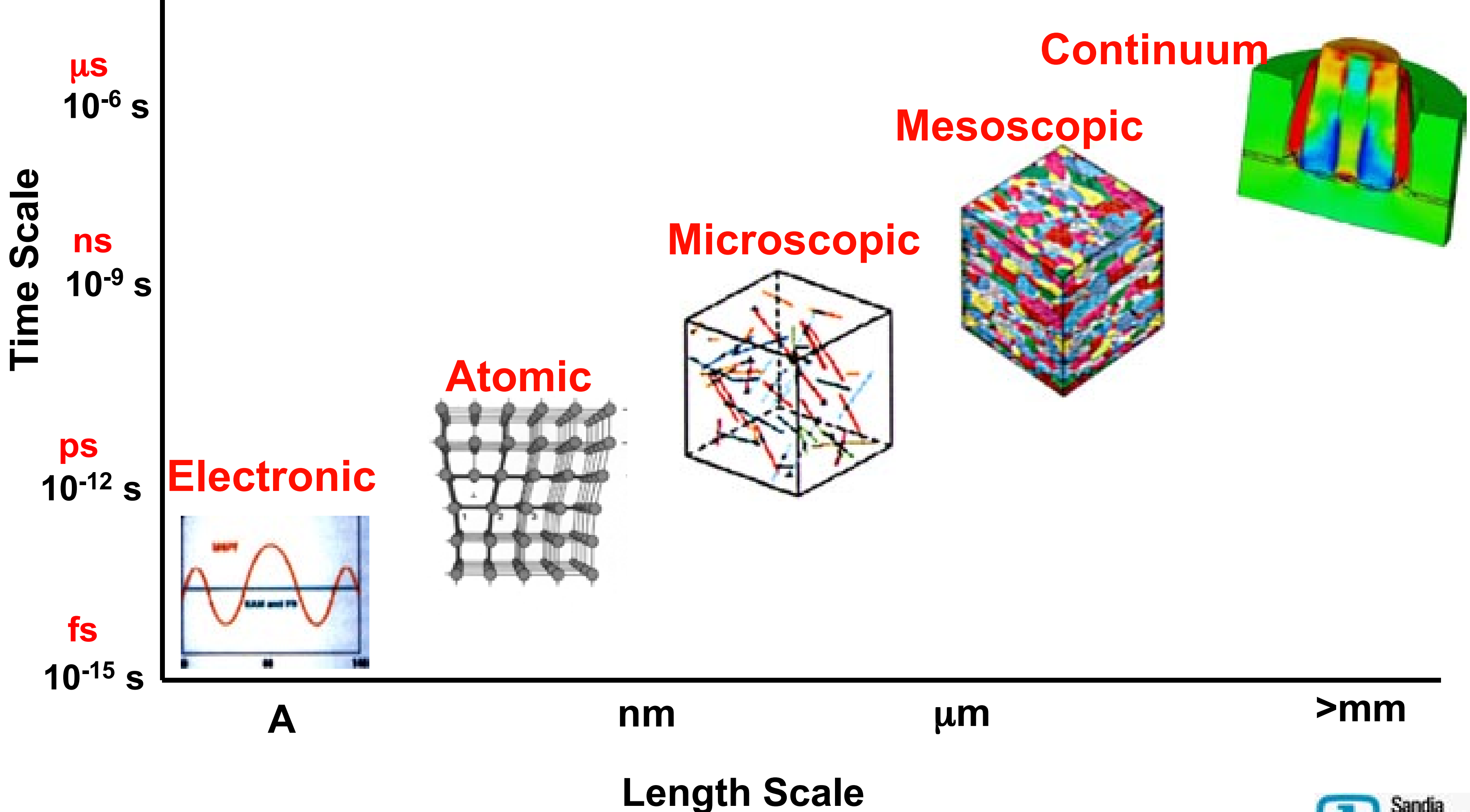

Sandia National Laboratories

Material science

Understanding mechanical properties requires measurements at each length scale

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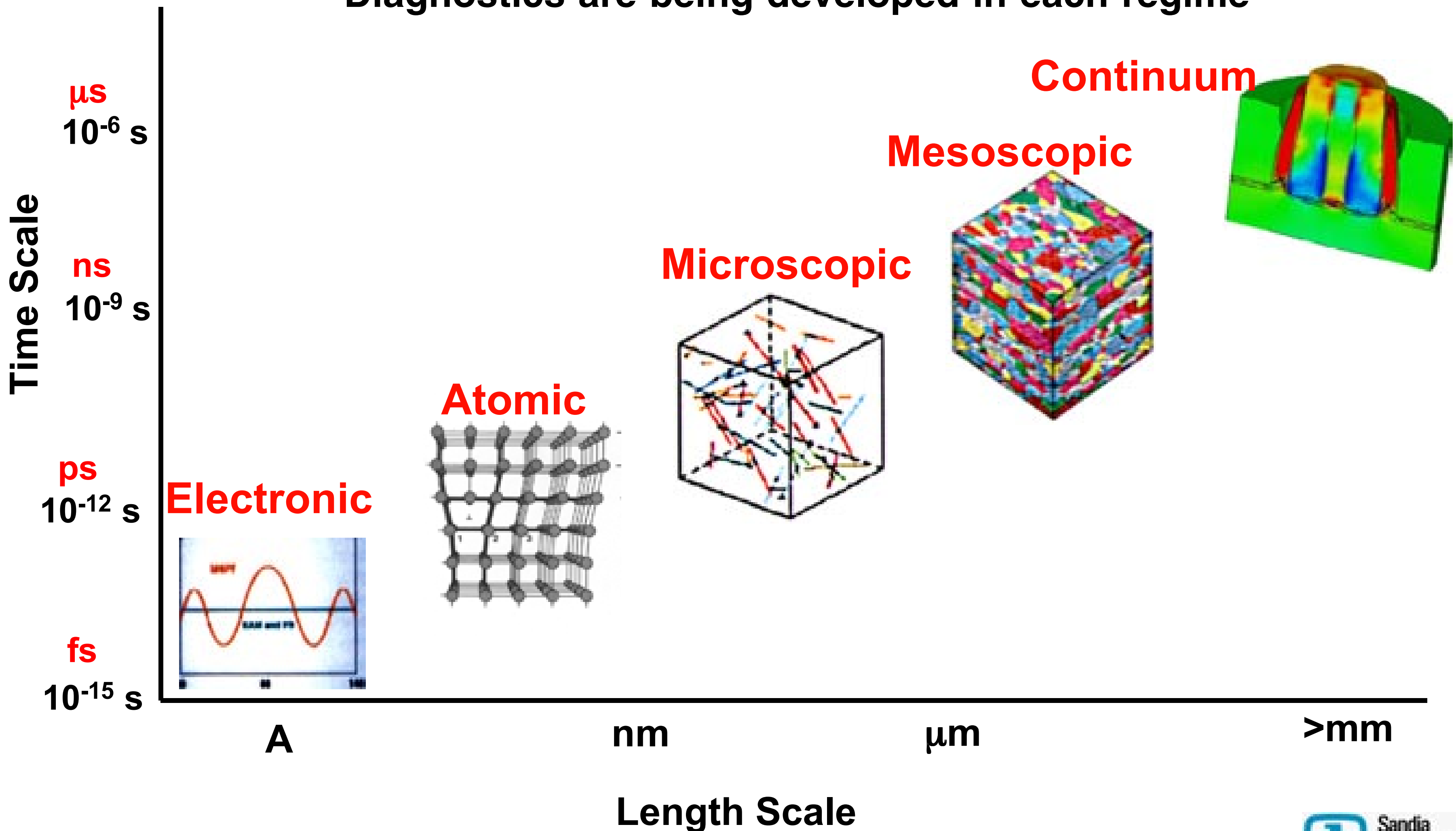

Material science

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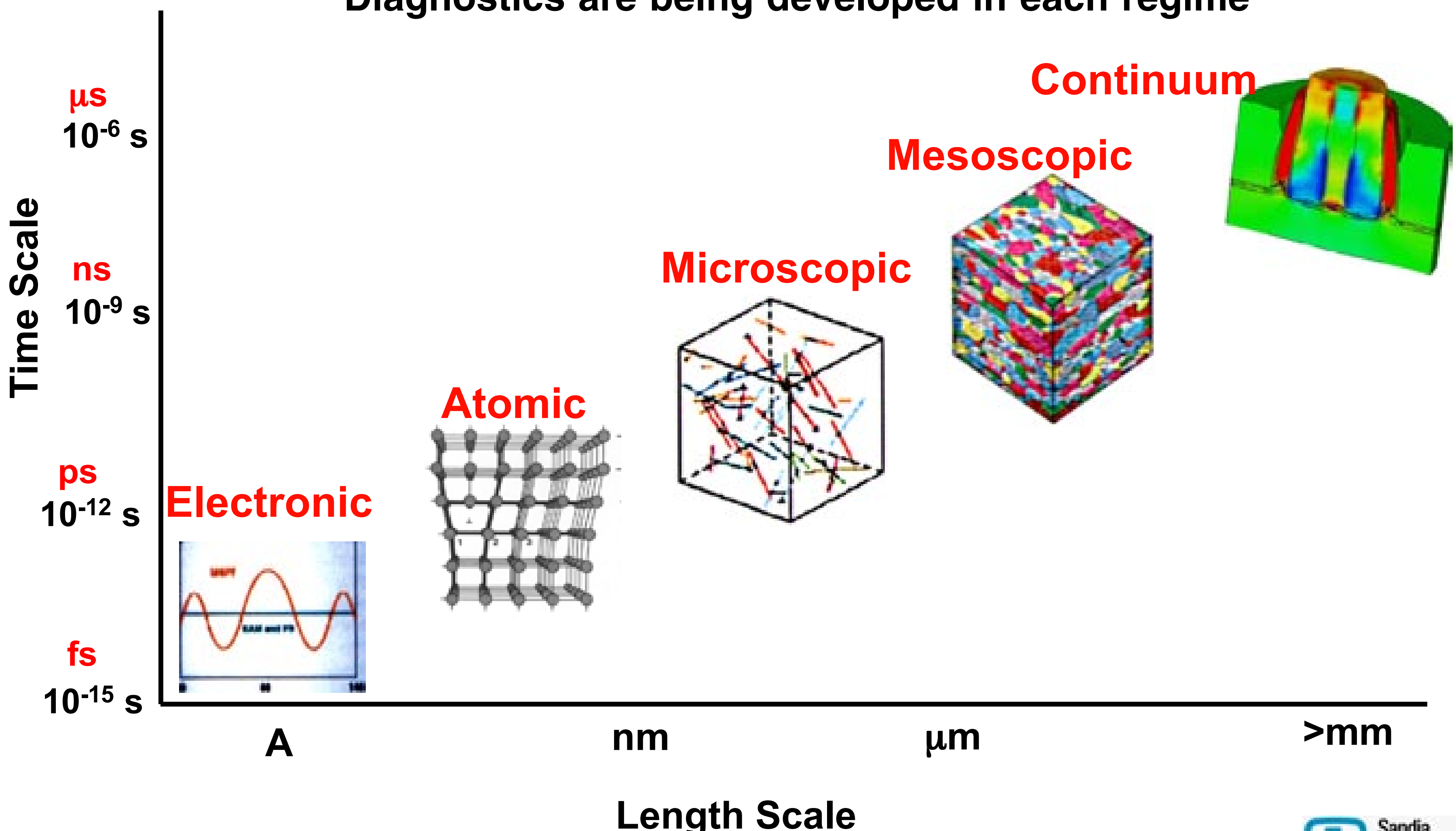
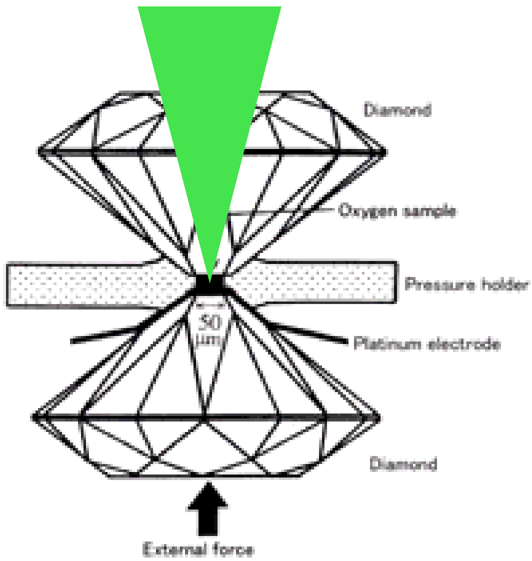


Sandia National Laboratories

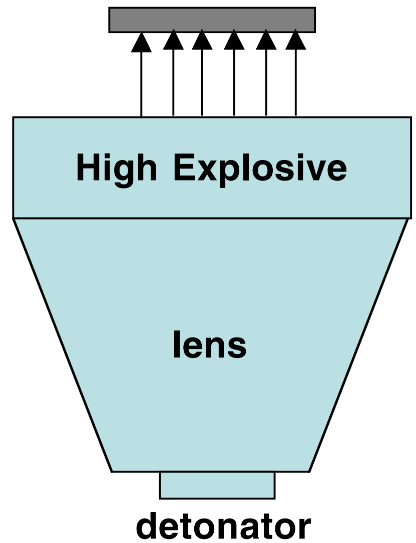
It is difficult to get above ~ 1 Mbar isentropically

- **Laser heated DACs get to ~ 3 Mbars, 4000 K in small samples**



- **Isotherm, then isochor**
- **Thermodynamic properties (P, T) + structure on a synchrotron**

- **High explosives get to ~ 1 Mbars for strength measurements**

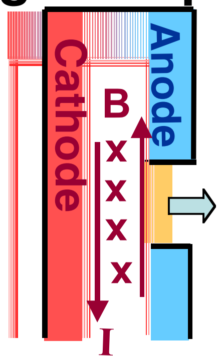


- **Isentropic**

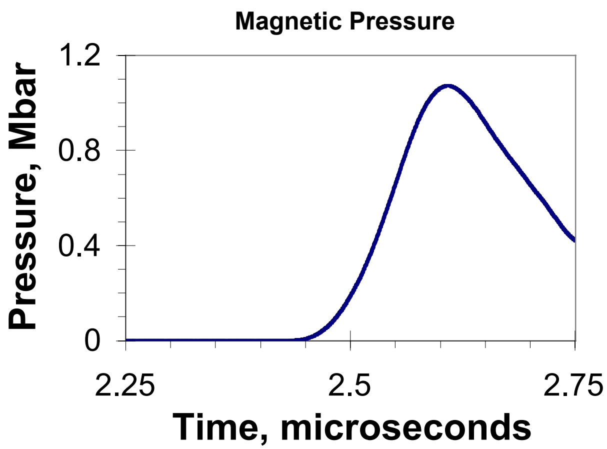
Barnes, JAP, 45, (1974); Rayevsky and Lebedev

Methods have been demonstrated to quasi-isentropically compress in the solid state to ~ 1 Mbar

Magnetic pressure



$$P = \frac{1}{2\mu_0} B^2$$



Hall, Phys Plas, 2069 (2000)

Kalantar, Phys Plas, 7 (2000)

Edwards, submitted to PRL

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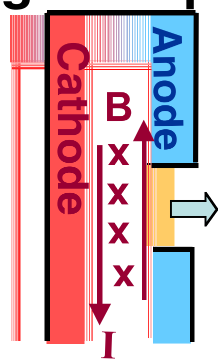

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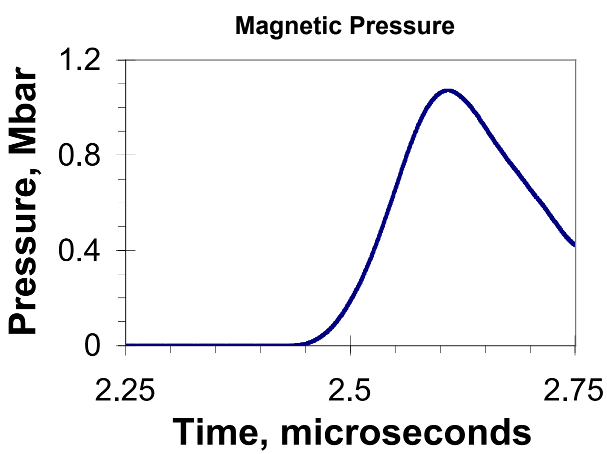
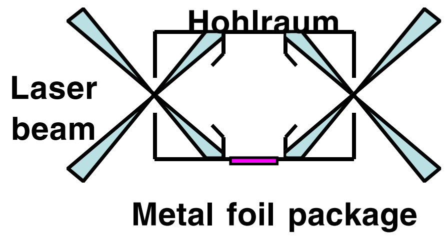
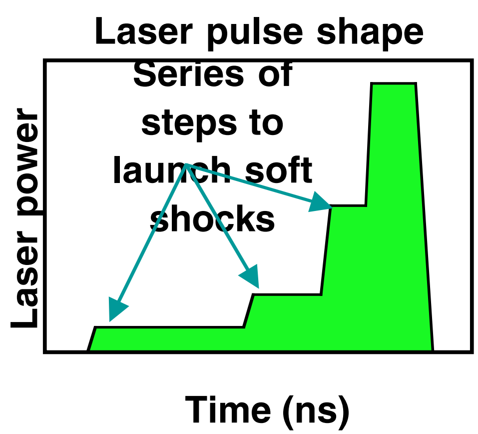


Laser driven hohlraum





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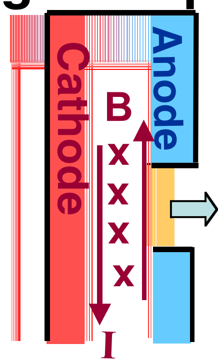

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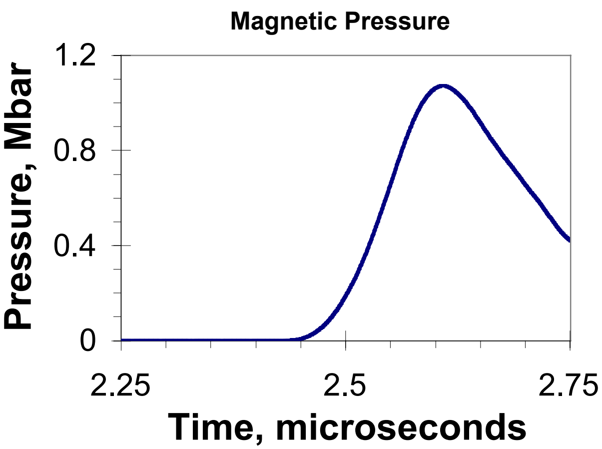
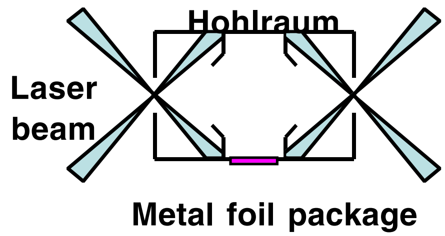
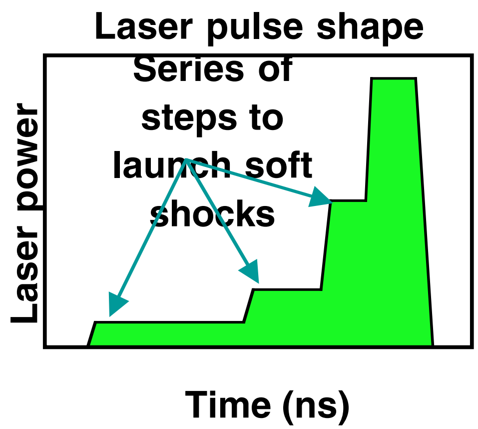
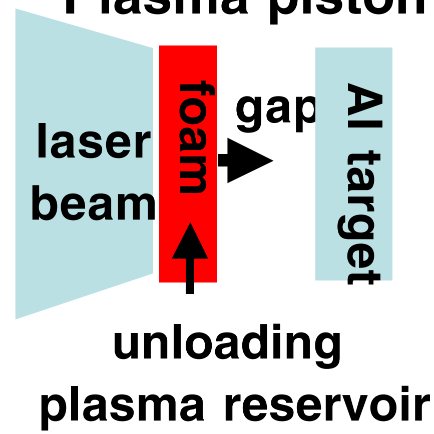


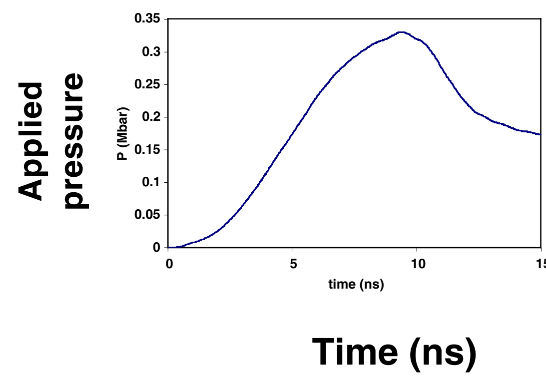
Laser driven hohlraum





Plasma piston





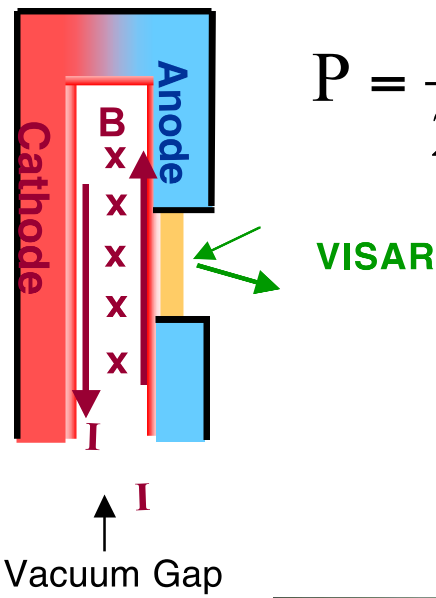
Hall, Phys Plas, 2069 (2000)

Kalantar, Phys Plas, 7 (2000)

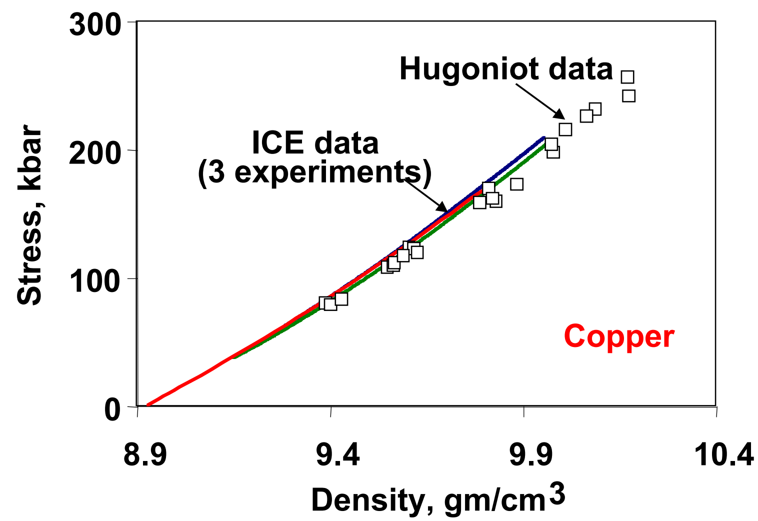
Edwards, submitted to PRL

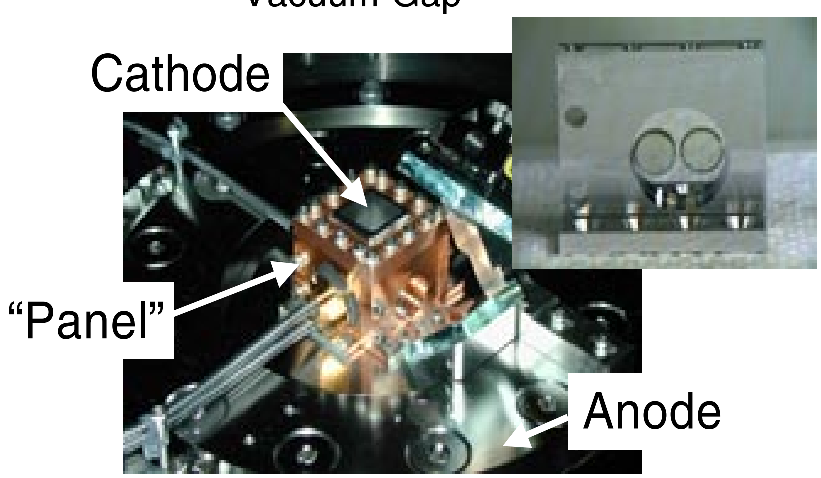
Atomistic

Measurement along an isentrope provides continuous equation-of-state data



$$P = \frac{1}{2\mu_0}B^2$$

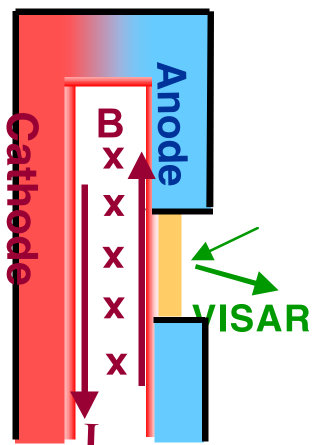




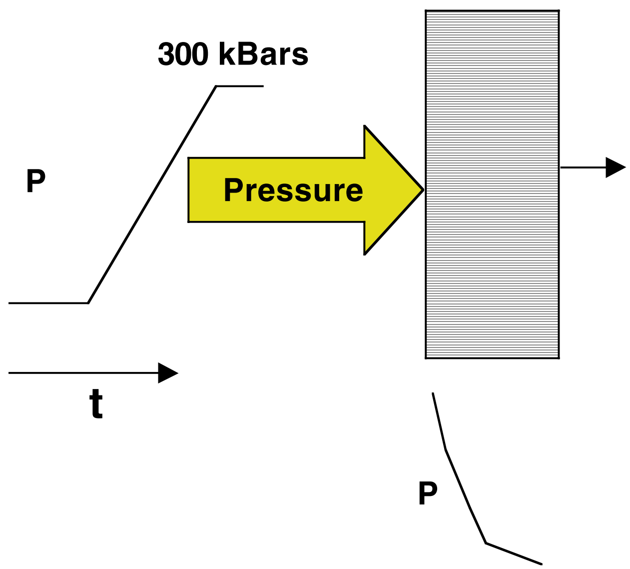
In comparison, a shock Hugoniot measurement provides 1 EOS datum per experiment

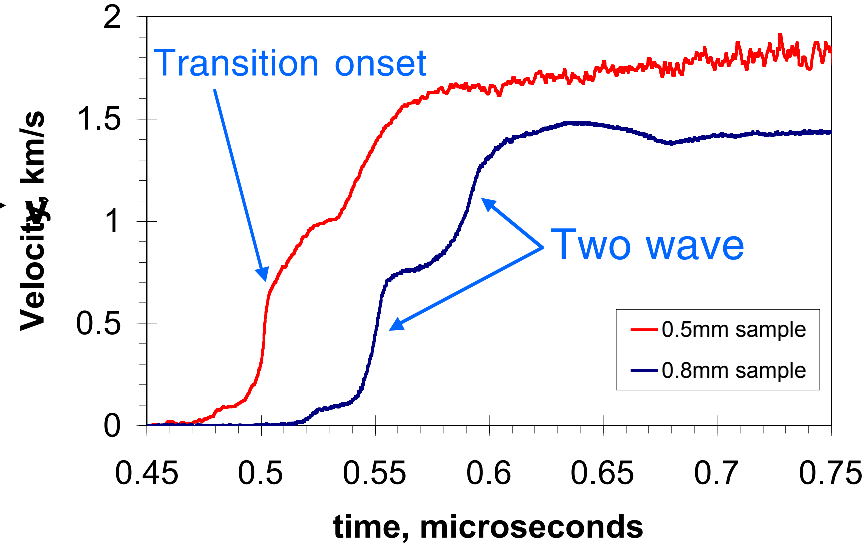
Reisman, Phys Plas 7 (2001)

A two wave structure is a signal of phase transition



$$P = \frac{1}{2\mu_0} B^2$$





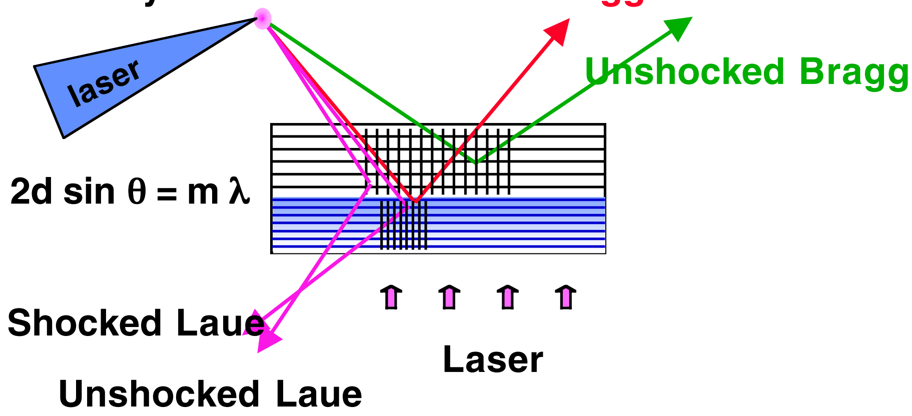
- **The solid to solid (bcc-hcp) phase change was measured in Fe on Z**
- **Modeling allowed transition time to be determined**

τ ~ 40 ns

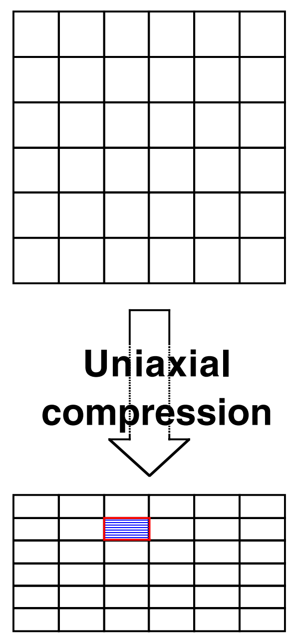
Hall, C. A. (2000). Physics of Plasmas **7**(5 PT2): 2069-2075.

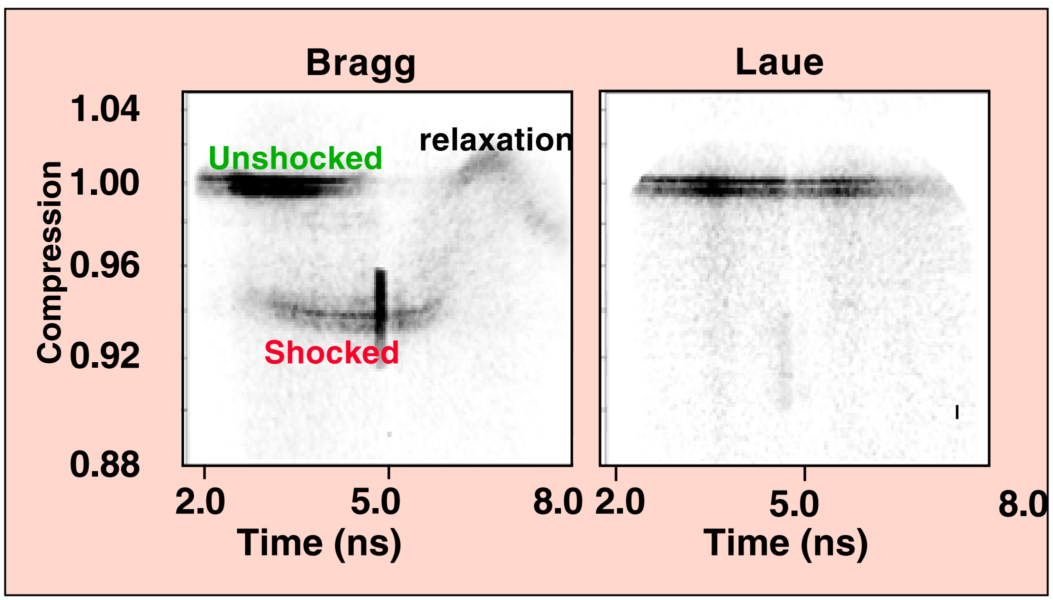
Atomistic

X-ray diffraction has been demonstrated to dynamically measure the lattice structure



- Si responds uniaxially on a ns time scale to compression 2x over elastic limit



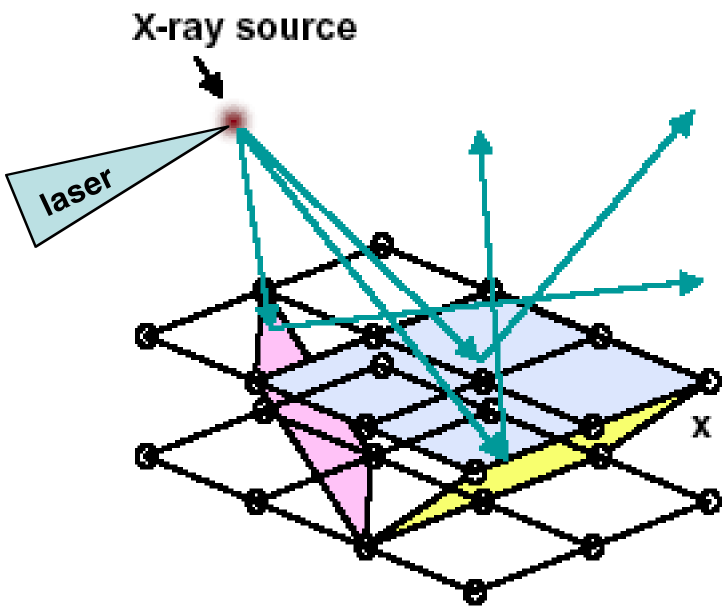


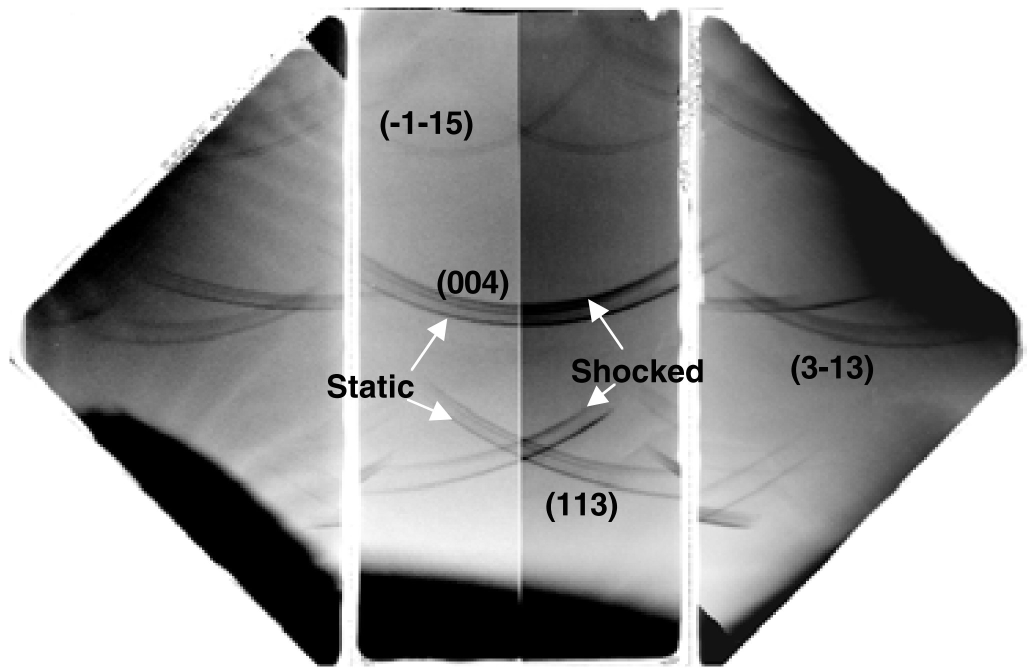
Loveridge-Smith, et al. (2001). Physical Review Letters **86**(11): 2349-2352.

Kalantar, D. H., et al. (1999). Review of Scientific Instruments **70**(1 PT2): 629-632.

Atomistic

The 3D lattice structure can be dynamically measured using a novel diffraction geometry

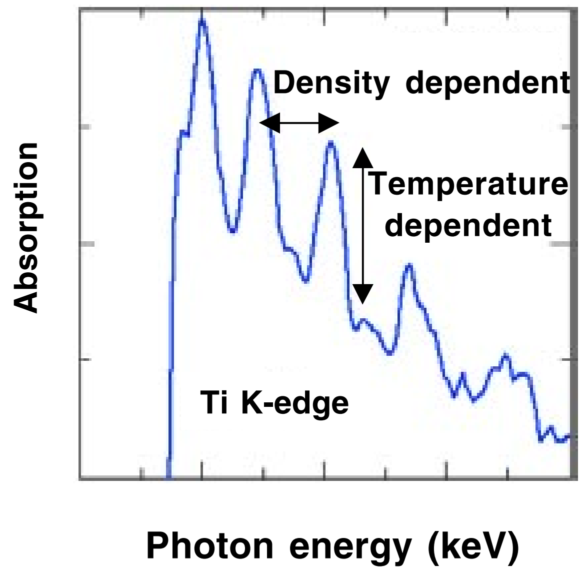


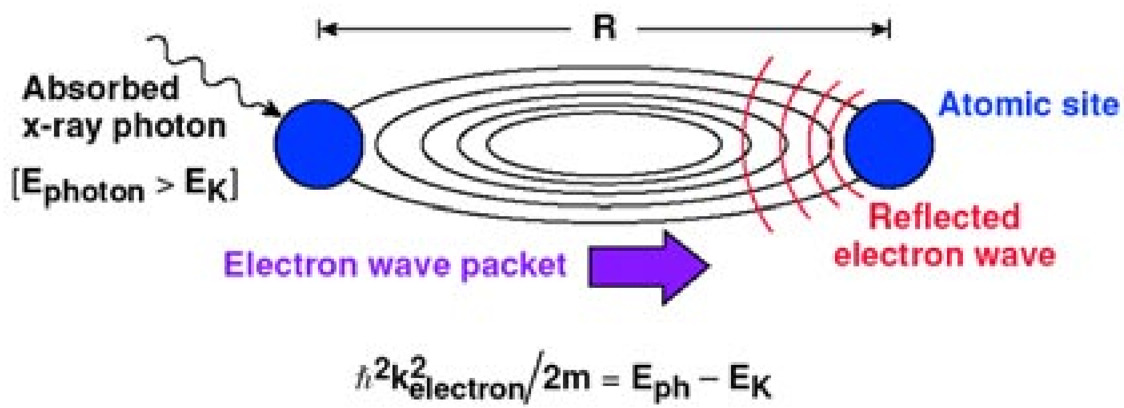


- **Time-resolved X-ray source allows 3D lattice structure to be measured under dynamic conditions**

Kalantar, Submitted to Phys Plas

Measurements of X-ray absorption near an edge provides information on density and temperature in a solid



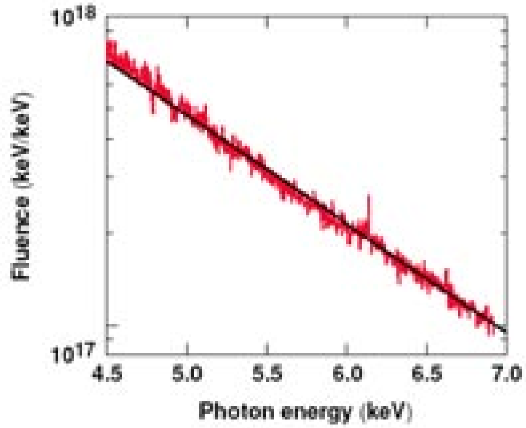


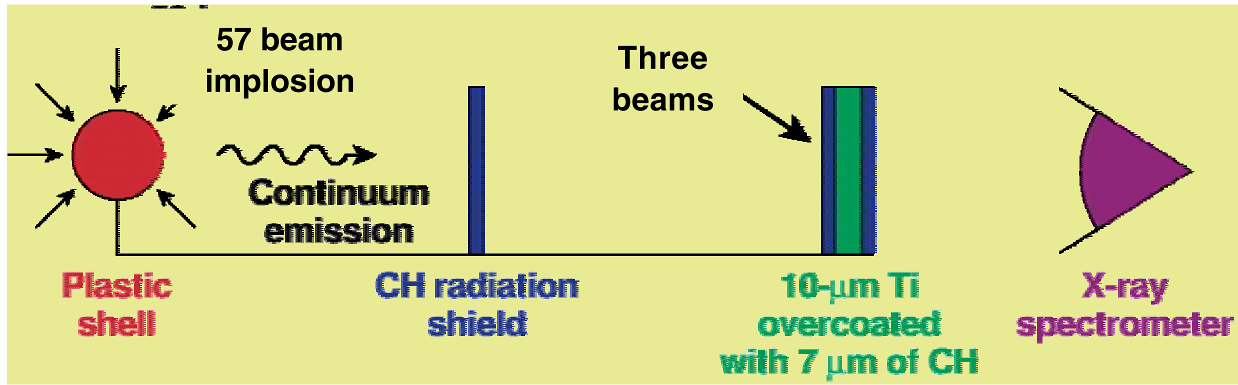
- EXAFS - interference of ejected electron waves with neighbors
  - Modulation ~ sin(2kR) => density
  - Amplitude of oscillations ~ $\exp[-2\sigma^2 k^2$
    - σ^2 is the Debye- Waller factor
    - $\sigma^2 \sim f(T/\rho^{5/2})$

EXAFS technique developed on a synchrotron is now being applied on a laser

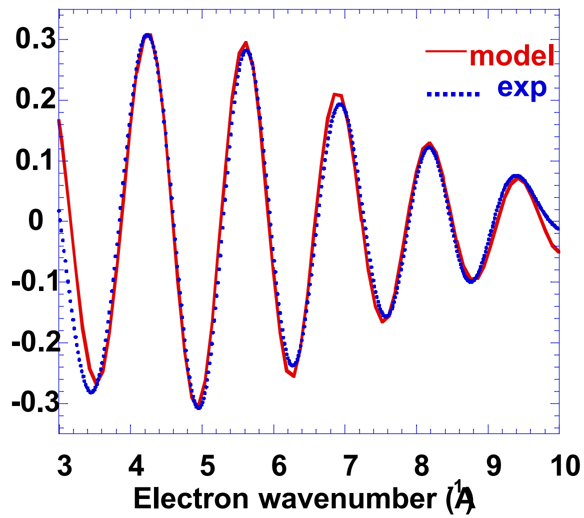
Atomistic

EXAFS provides a way to measure T to 20-30% for isentropically compressed targets

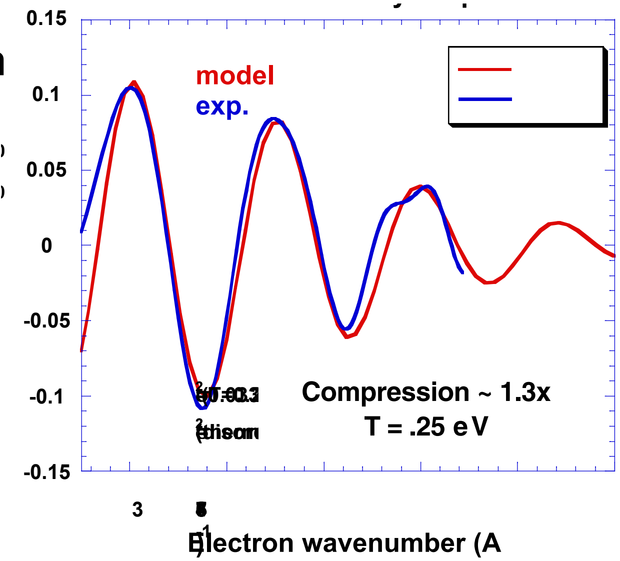




Undriven target



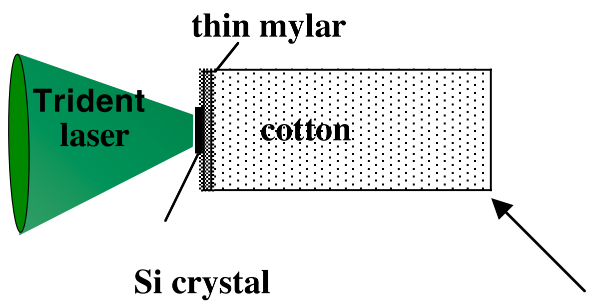
Driven target



- A capsule is imploded on the Omega laser to provide a continuum source for EXAFS diagnosis of a target

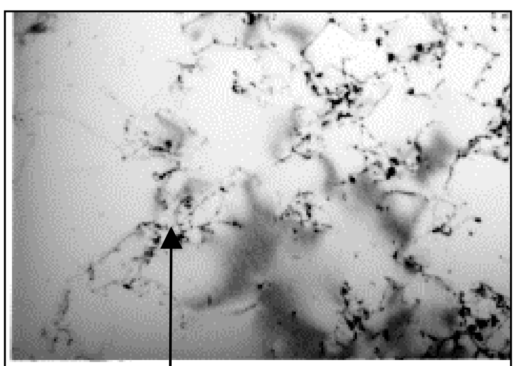
Yaakobi, tobe submitted to Phys Plas

Recovery of compressed samples and metallurgical analysis show identical features to those shocked on a gas gun



A filled tube slow down and capture samples

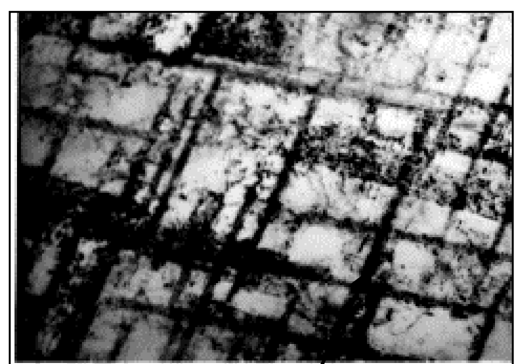
—Laser shocked samples have identical features to samples shocked on gas guns at the same pressure



40 J, Cu
130 kbar

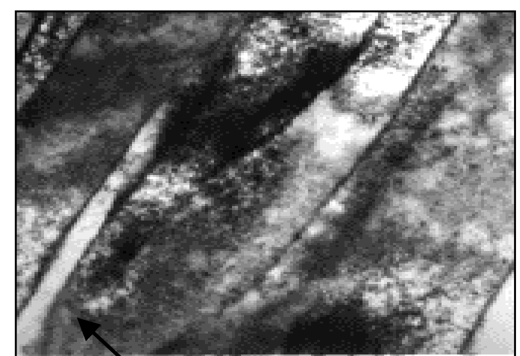
Dislocations

0.5 μm



205 J, Cu
400 kbar

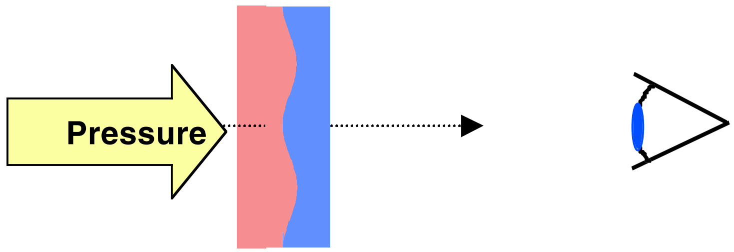
Micro-twins



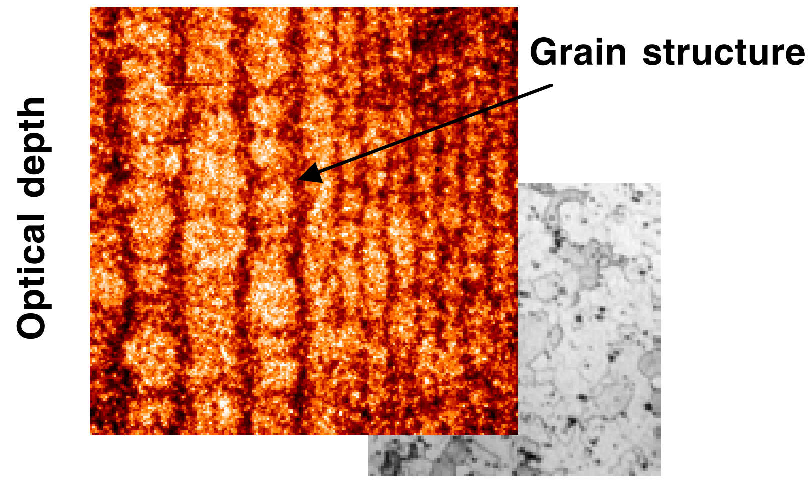
320 J, CH/Cu
1.4 Mbar

Twinning

Strength in Al was inferred from measurements of Rayleigh-Taylor instability growth on Nova at ~ 1.4 MBars



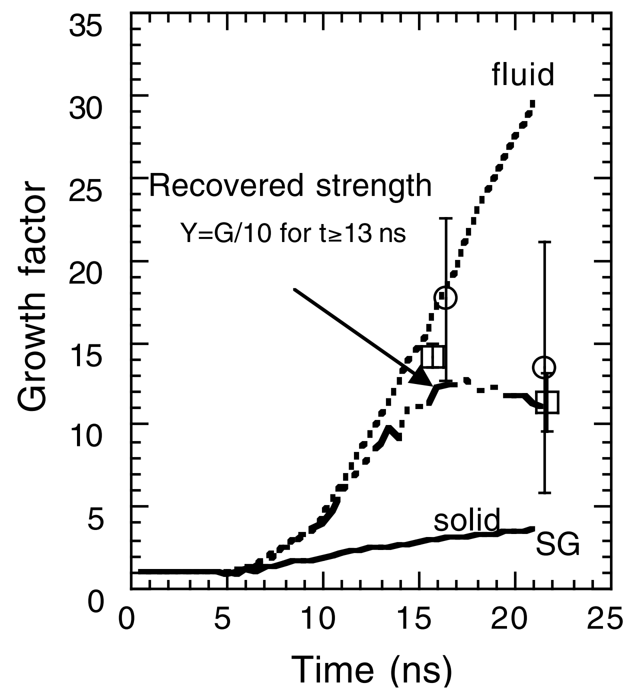
Laser generated X-rays isentropically compress



Growth rates with strength are expected to be reduced from classical (fluid)

Grain structure can be measured

Data does not agree with predictions

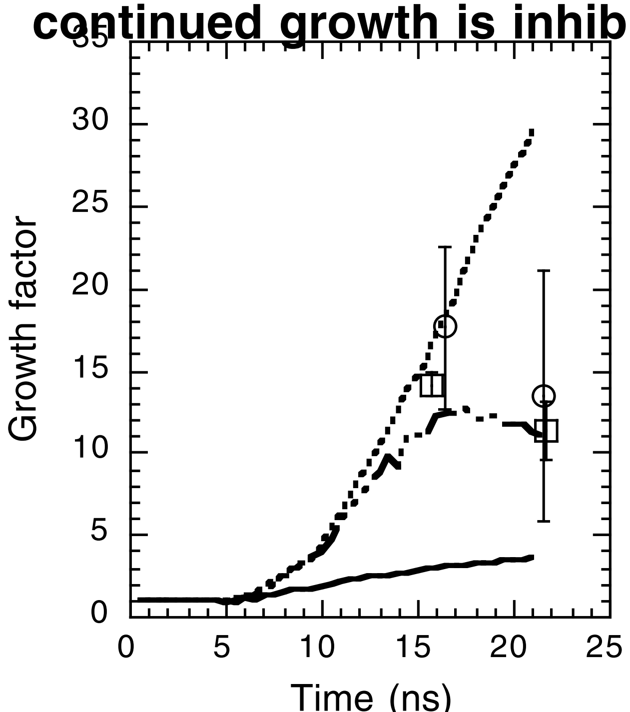


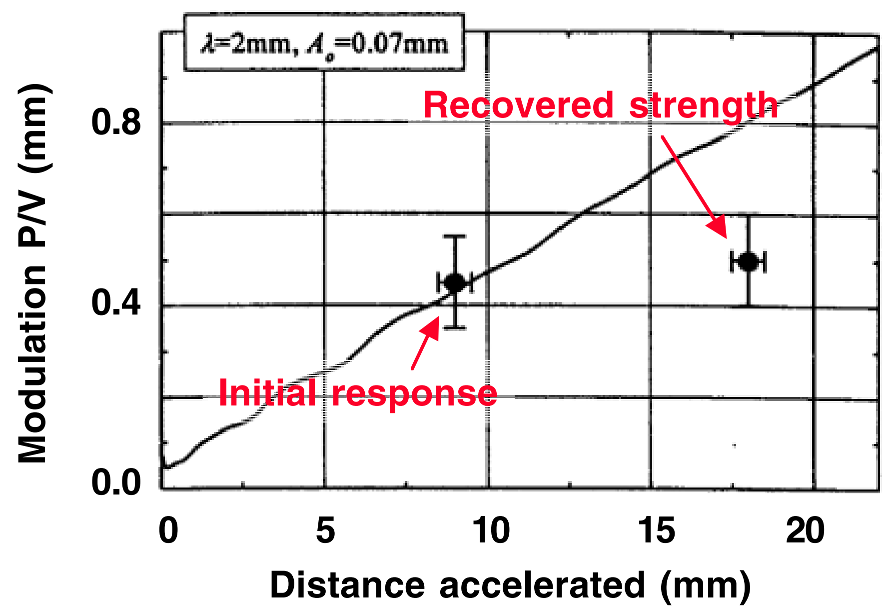
Kalantar, D. H., et al. (2000). Physics of Plasmas **7**(5 PT2): 1999-2006.
Kalantar, D. H, et al. (2000). ApJS **127**(2): 357-363.

Continuum

The RT growth is nearly fluid at early times, but it is suppressed at later times

- Suggestive of data by Rayevsky/Lebedev
- High pressure strain causes localized heating and softening in shear bands; bulk Al flows as fluid due to deformation in these localized regions
- As heat dissipates the metal regains bulk solid strength and continued growth is inhibited



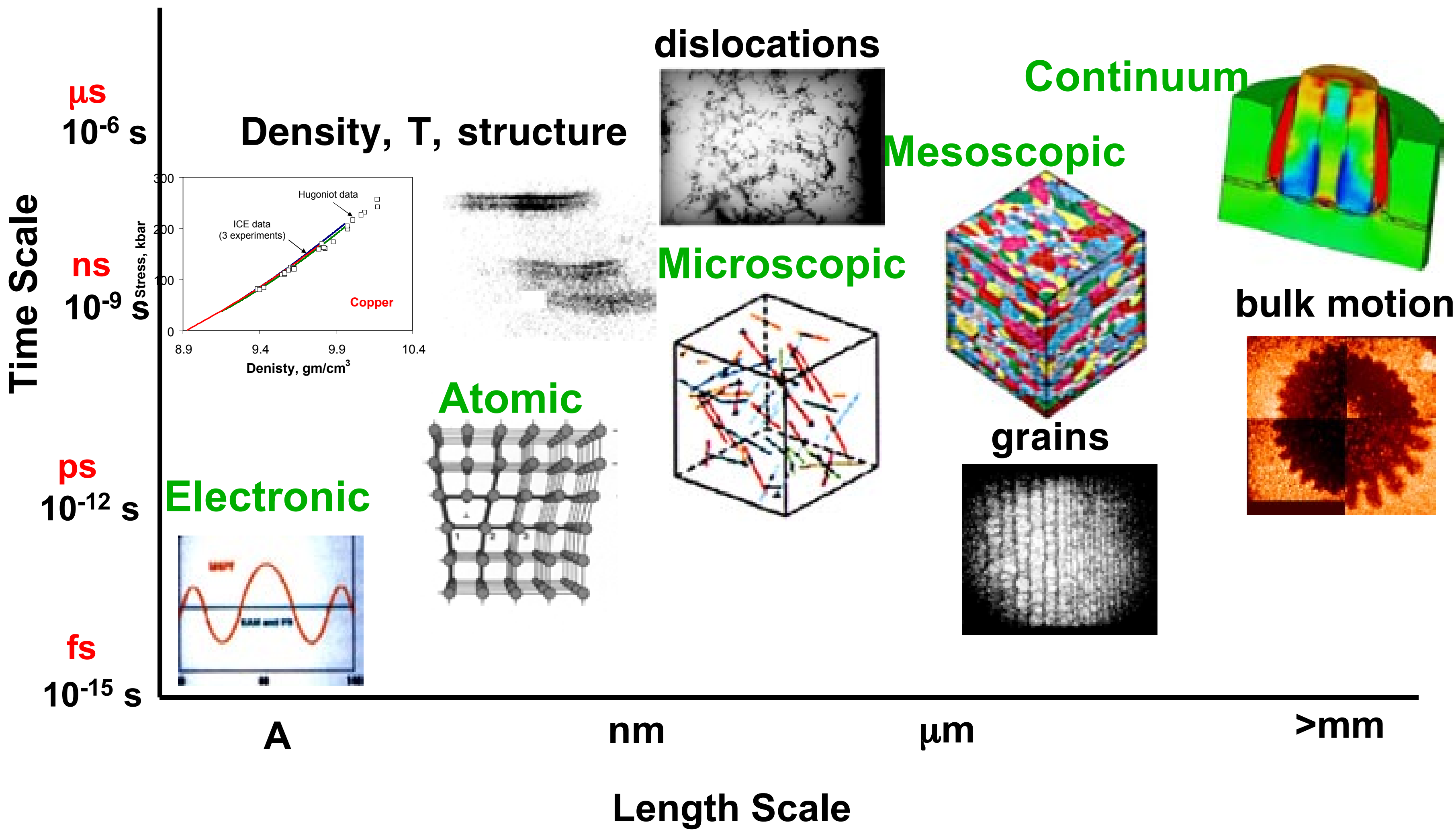


New data in new regimes => surprises

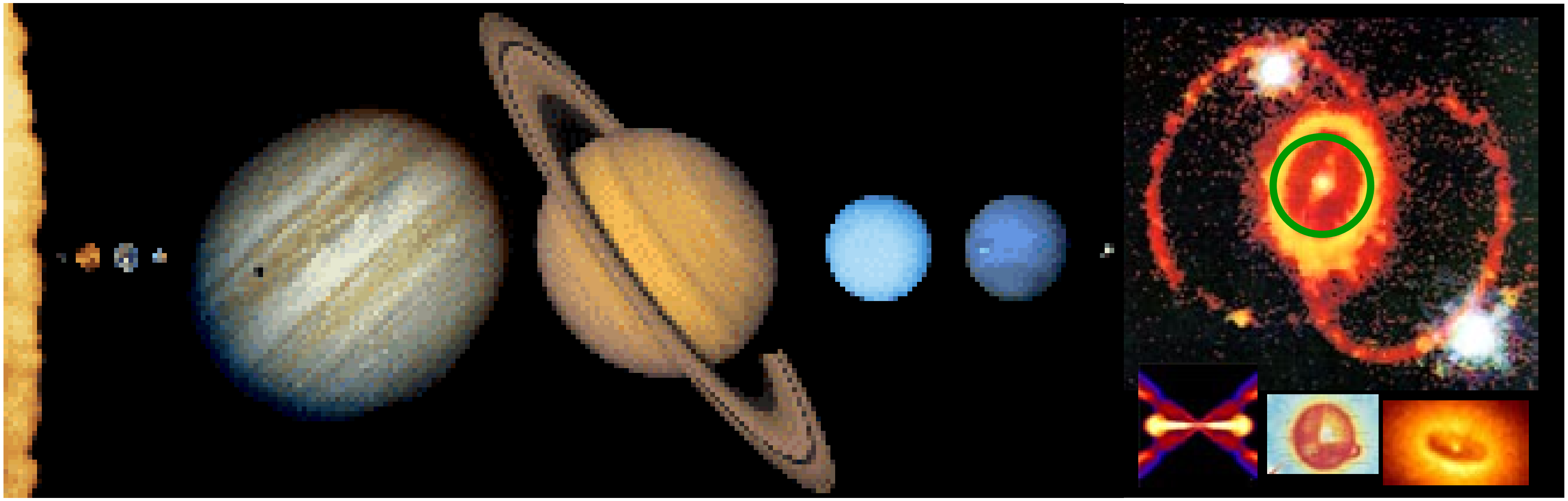
Rayevsky *et al*, IWPCTM, 1999.

Material science

The tools are in place to perform quantitative experiments at high isentropic pressures



Outline

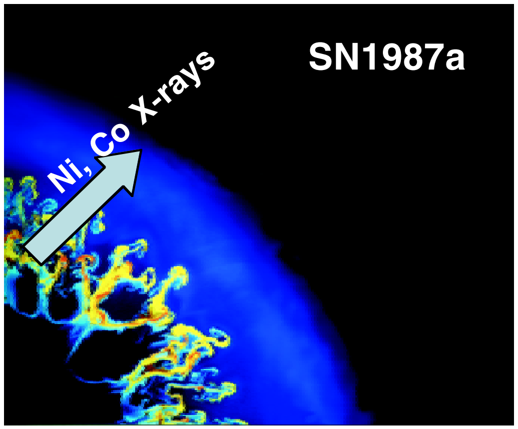


- **Significant advances in high energy density physics**
  - *Hugoniot equation-of-state*
  - *Materials science at high pressure*
  - *Hydrodynamics*
  - *Radiation transport and atomic physics*
- **Future directions**

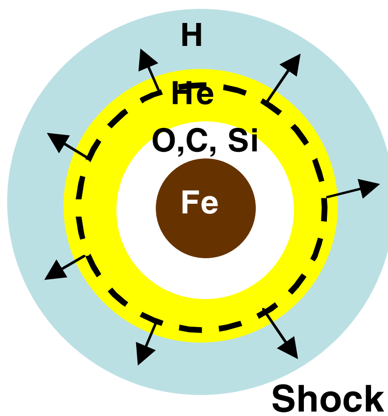
Hydrodynamics

Hydrodynamic instabilities may play a role in understanding data from supernova 1987a

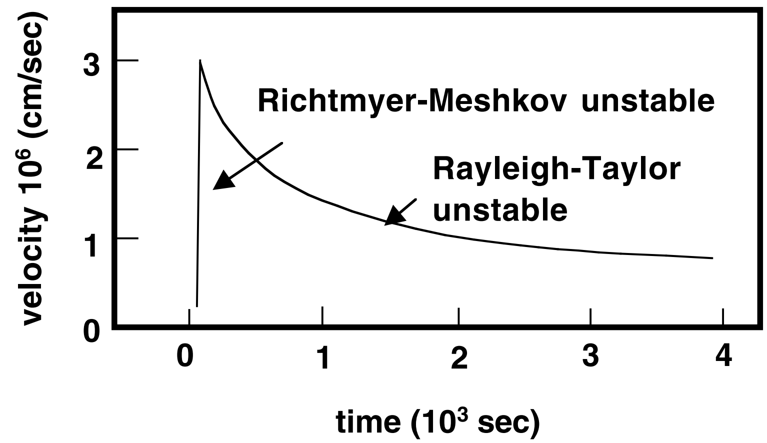
Numerical simulations of SN 1987A do not reproduce measurements

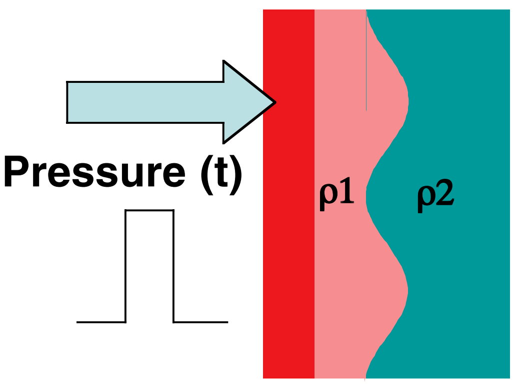


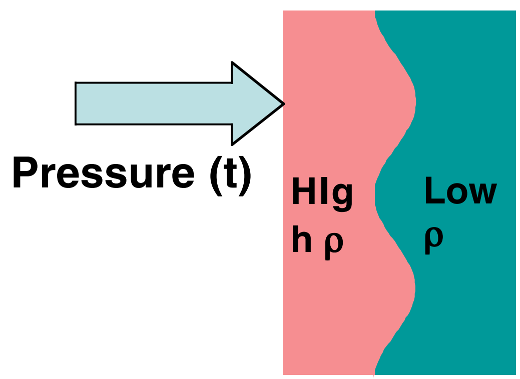
"Onion skin" model



He-H interface





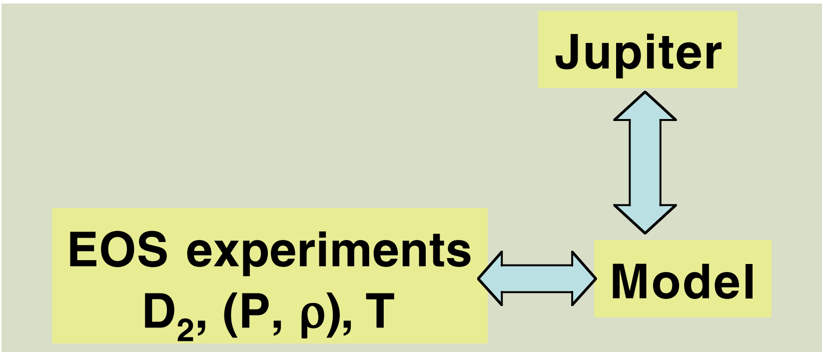


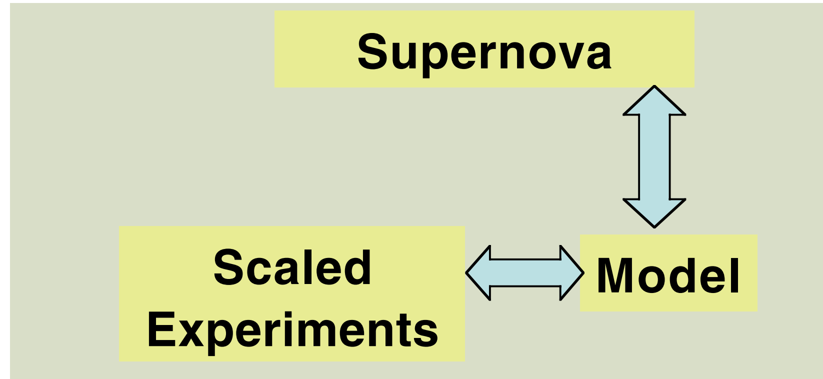
The Richtmyer-Meshkov instability occurs at an interface impulsively accelerated by a shock

The Raleigh-Taylor instability occurs at an interface when a heavier fluid decelerates against a lighter one

How does one test complex dynamical phenomena?

Hydrodynamics can be tested in dynamical models with scaled experimental testbeds





- The dynamical behavior of a system described by Eulers' Equations

$$\frac{\partial \boldsymbol{P}}{\partial \boldsymbol{t}} - \gamma \frac{\boldsymbol{P}}{\rho}\frac{\partial \rho}{\partial \boldsymbol{t}} + \mathbf{v} \bullet \nabla \boldsymbol{P} - \gamma \frac{\boldsymbol{P}}{\rho}\frac{\partial \rho}{\partial \boldsymbol{t}} \mathbf{v} \bullet \nabla \rho = \mathbf{0}$$

$$\frac{\partial \mathbf{v}}{\partial \boldsymbol{t}} + (\mathbf{v} \bullet \nabla)\mathbf{v} = -\frac{\nabla \boldsymbol{P}}{\rho} \qquad \frac{\partial \rho}{\partial \boldsymbol{t}} + \nabla \bullet (\rho \mathbf{v}) = \mathbf{0}$$

is invariant under any scale transformation that preserves

$(h/\tau)\sqrt{(\rho/P)}$ ~ Mach #

provided viscosity and thermal and radiative transport can be neglected

Hydrodynamical evolution is scaled for scale sizes ~ $\rho/|\nabla\rho|$

* Ryotov et. al, Ap. J, 518, p. 821 (1999)

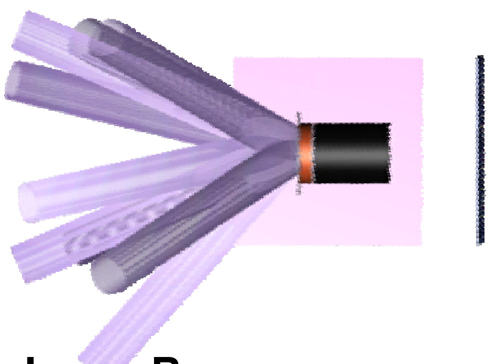
Practical implementation of scaling requires precise control over experimental conditions

1. Tailored pressure history

$$(h/\tau)\sqrt{(\rho/P)}$$

2. Scaled initial conditions
=> Solid materials easier
Geometry

3. Compressible materials
=> Ionized



Laser Beams
=> Pressure (t)

Kane, ApJ, 365 (2000)

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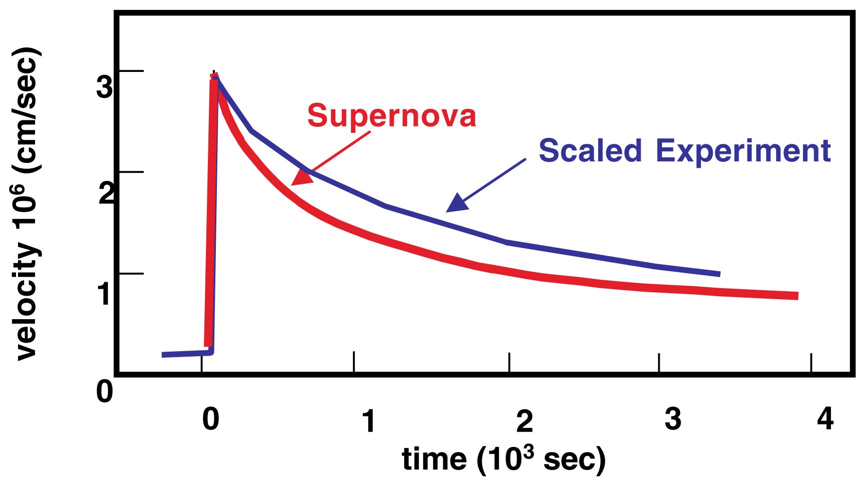

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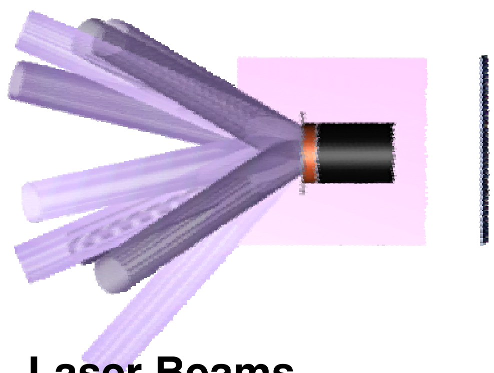

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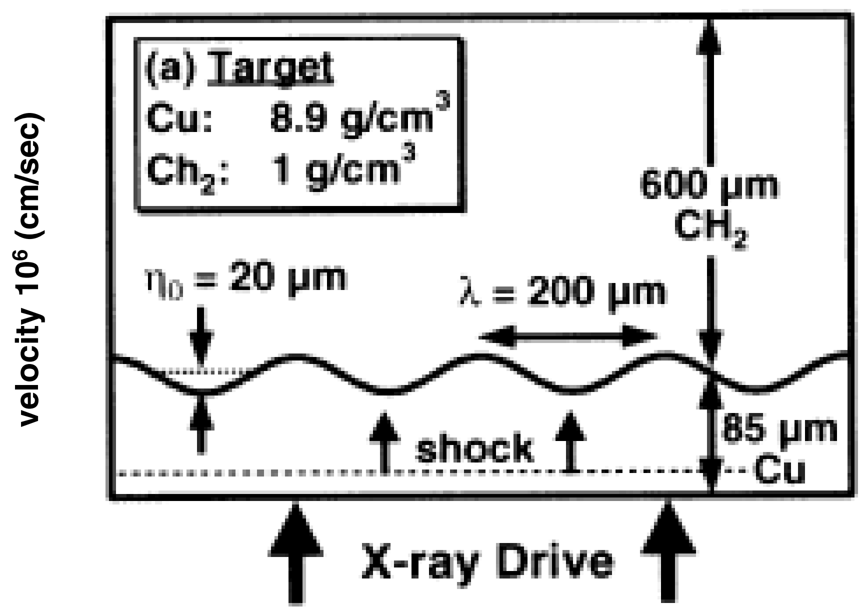
=> Pressure (t)



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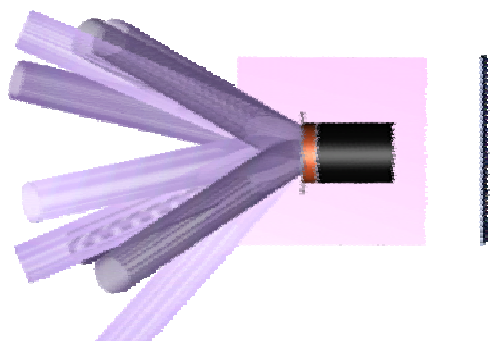

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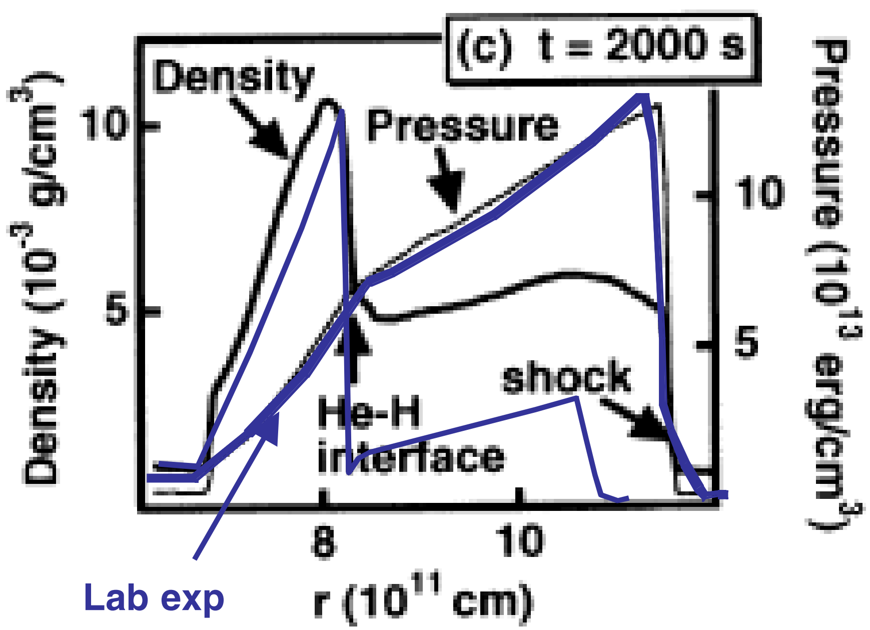
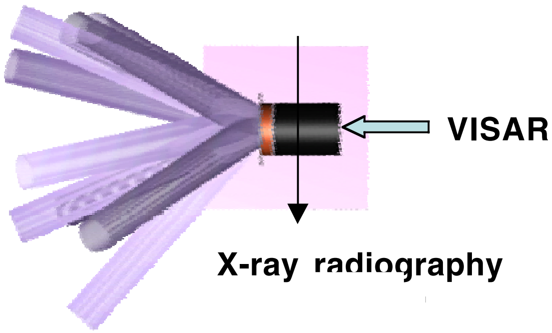


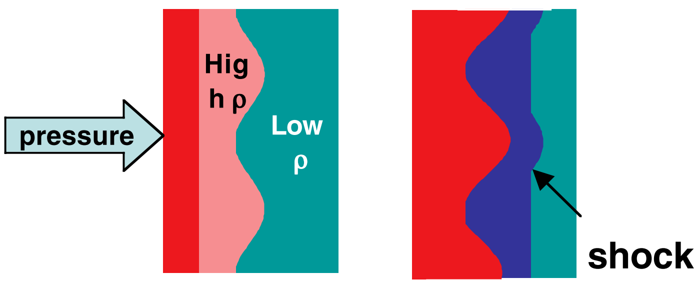
Kane, ApJ, 365 (2000)

Hydrodynamics

High Mach number RM experiments measured reduced growth due to shock proximity

Laser driven shock tube Mach ~ 10





- Incompressible models (Sadot, 1998) predict that spike tip moves faster than shock
- Precise experiments can be done on laser driven shock tubes and compared to analytical models

Glendinning et. al., submitted to PRL

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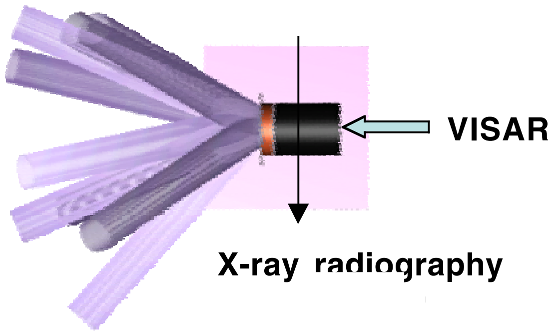

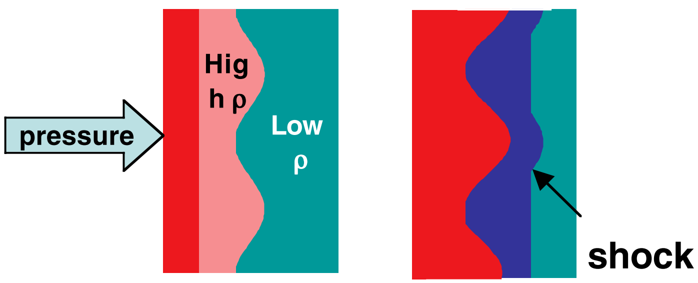

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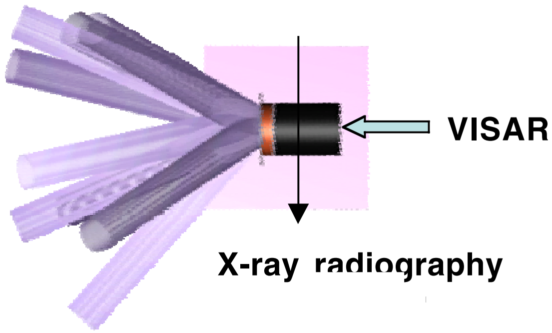

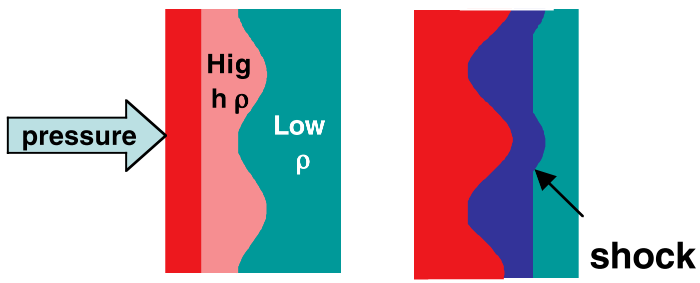

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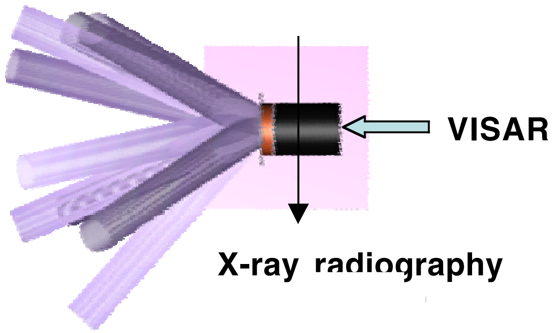

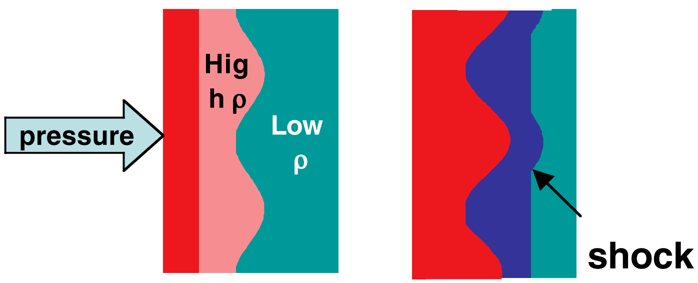

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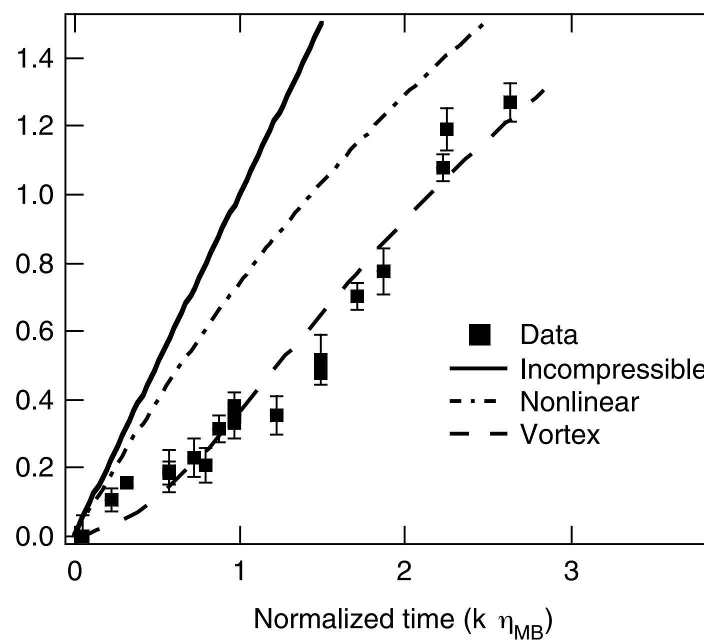
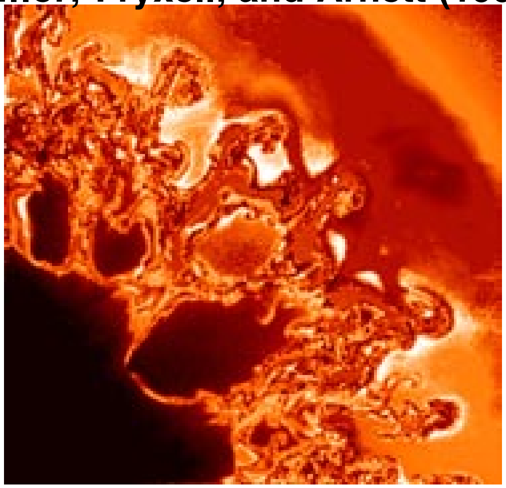


Glendinning et. al., submitted to PRL

Hydrodynamically scaled SN instability experiments have been performed on Omega

2D simulation of SN1987A
Muller, Fryxell, and Arnett (1991)



Physics was piecewise separated and scaled experiments were compared to modeling

Remington, B. A., R. P. Drake, et al. (2000). Physics of Plasmas **7**(5 PT2): 1641-1652.

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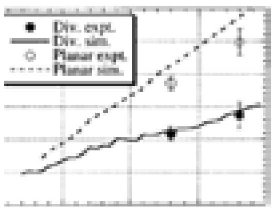
Spherical divergence



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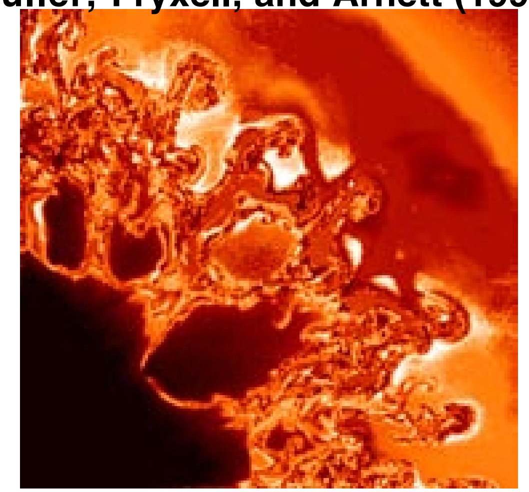

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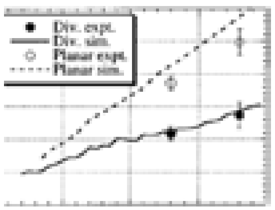

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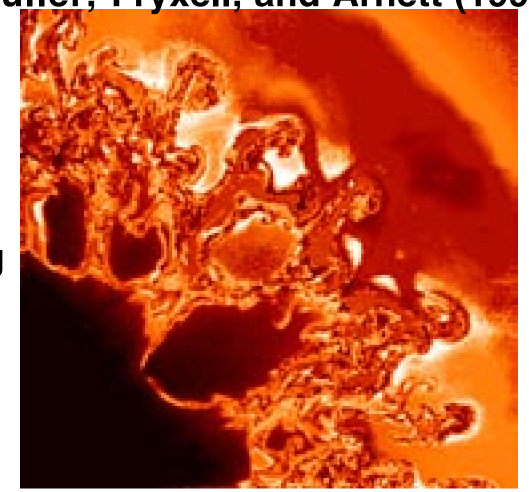
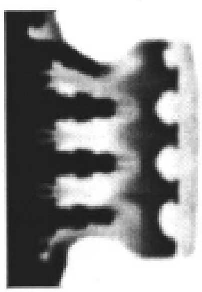


Multi-interface coupling



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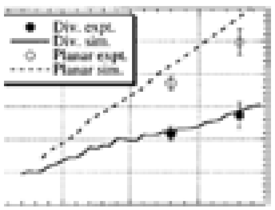

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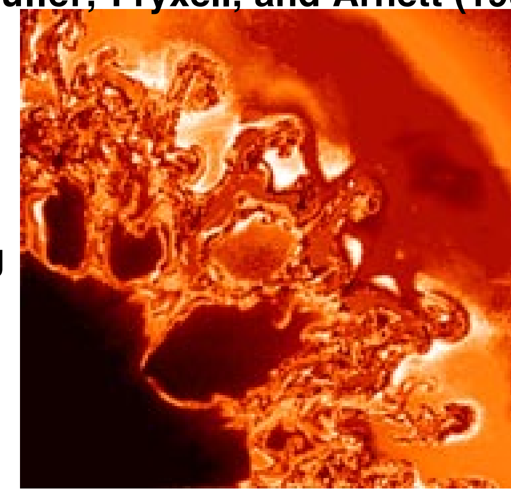
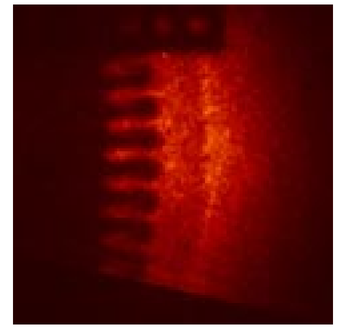
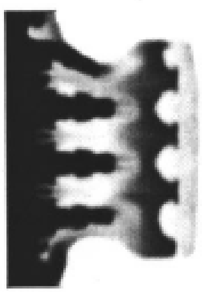


2D vs. 3D instability



20% growth
vs ~ 30%
expected

Multi-interface coupling



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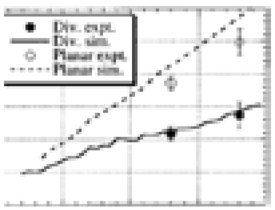

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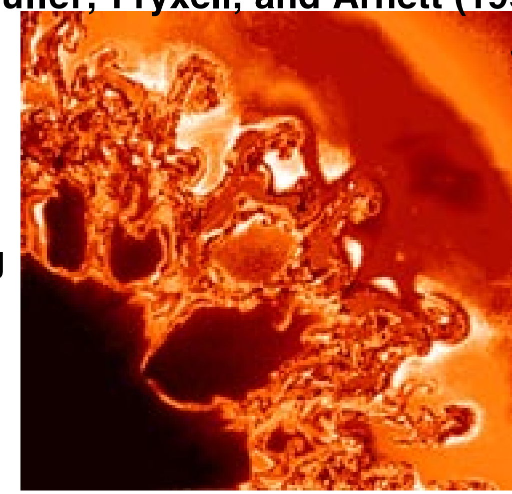

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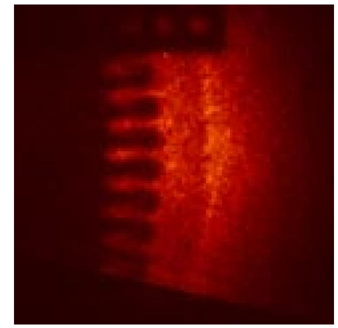
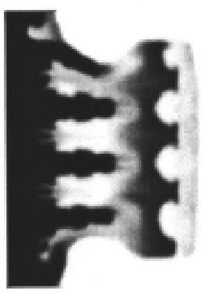
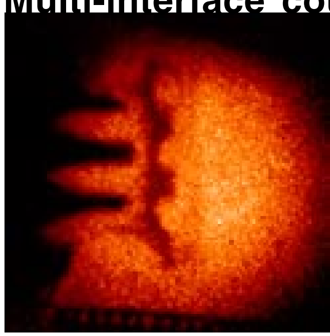


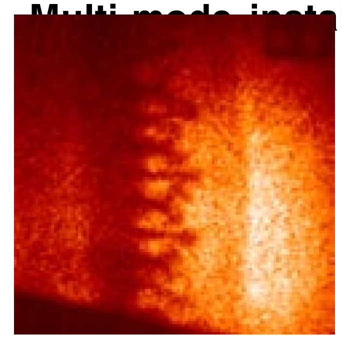
20% growth vs ~ 30% expected

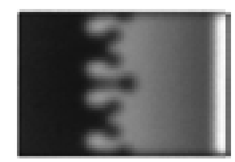
Multi-interface coupling





Multi-mode instability





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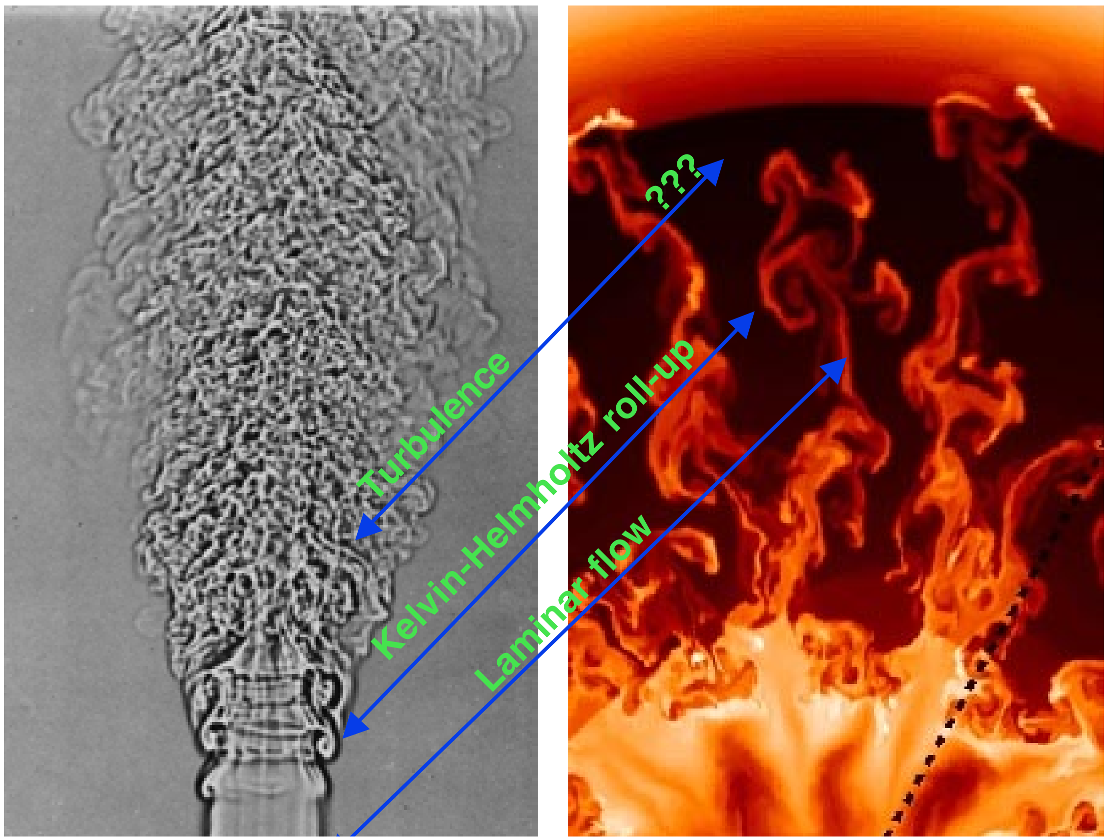
Large scale physics can be tested, but what about small scales?

Simulations of supernova explosions do not appear to be turbulent



Data of a Re = 10^4 flow

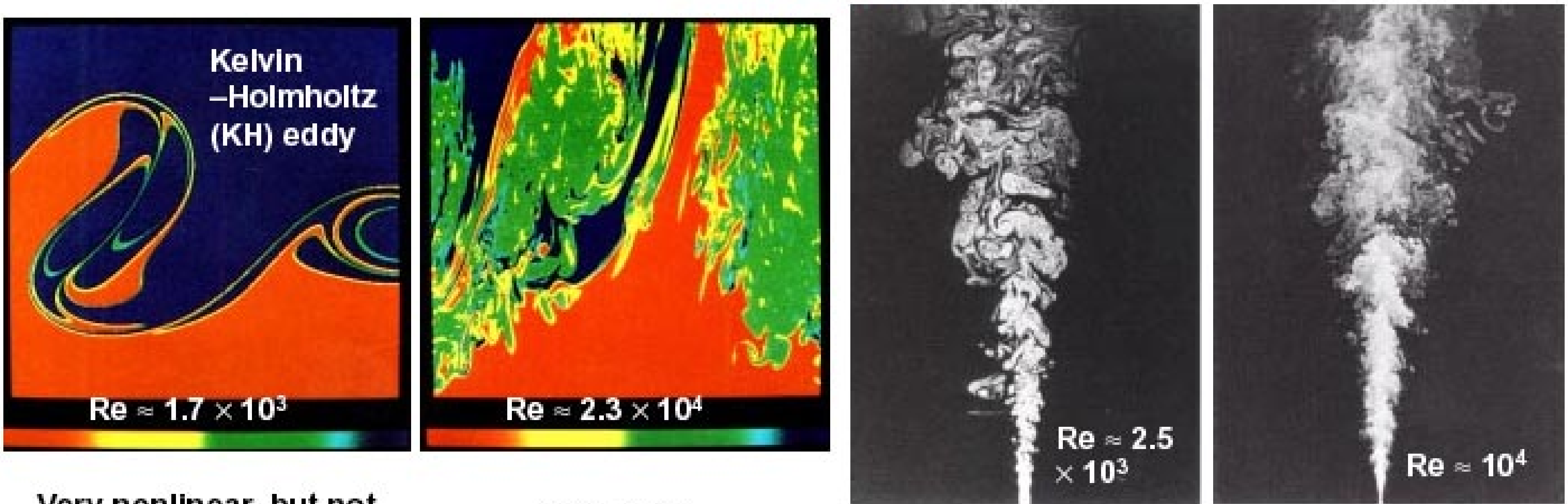
SN simulations of Re = 10^{10} hydrodynamics

- **Turbulence will affect mixing**
  - *Linear RM ~ t*
  - *Turbulent RM ~ $t^{.5-1}$*

Re = inertial/viscous = Lv/viscosity

A universal “mixing transition” at Reynolds number ~ 2 x10^4 was proposed - physics is same afterwards

“Steady” State



Very nonlinear, but not atomically mixed

Turbulent, atomically mixed

Turbulent, but not atomically mixed

Turbulent, atomically mixed

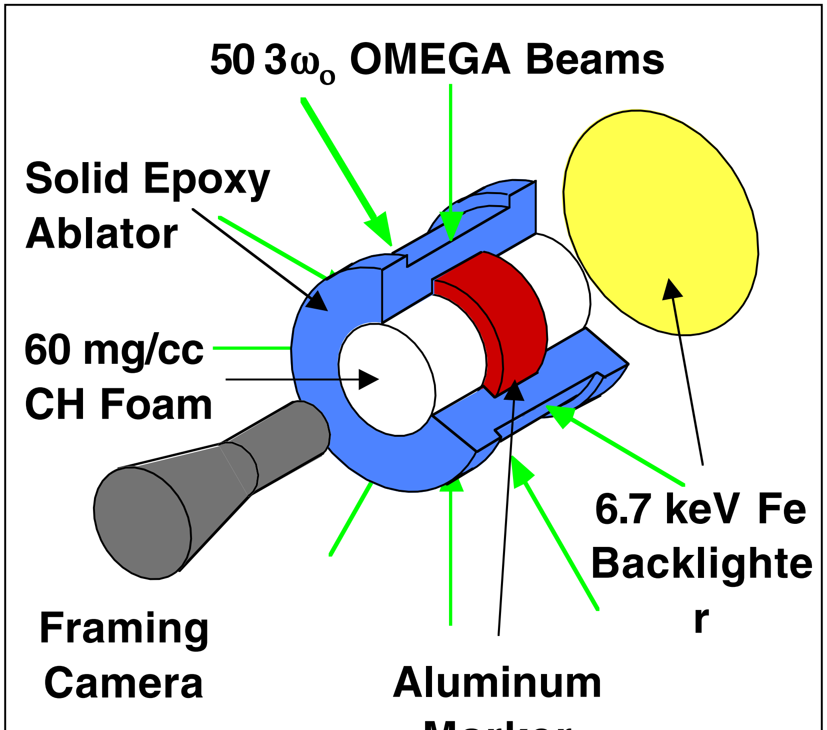
For dynamical systems, it is proposed to generate the scales needed, time > (L/v) x 100 $Re^{-.5}$

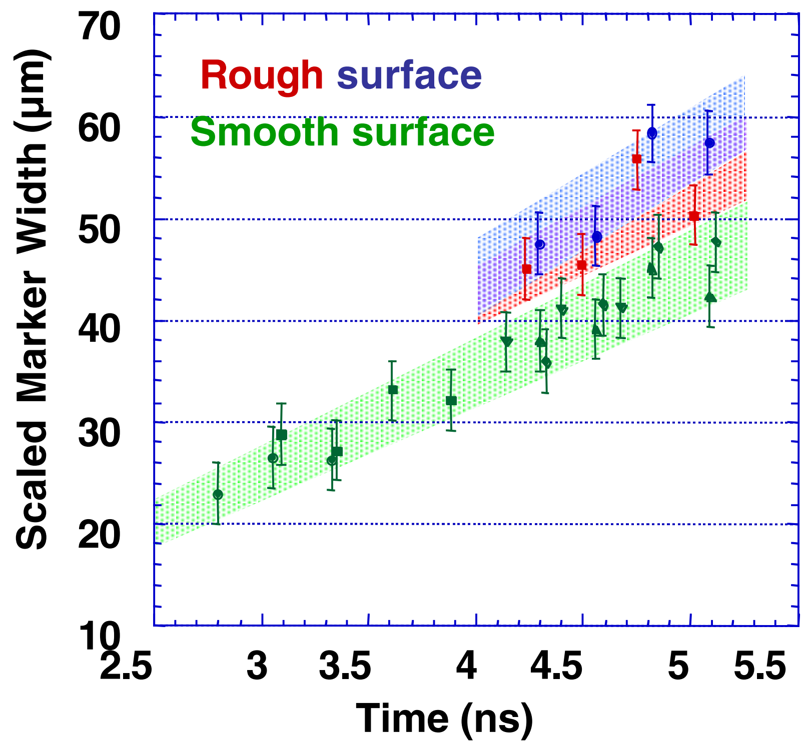
Driving, diagnosing and modeling the transition to turbulence in compressible high Reynolds number flows is the next challenge

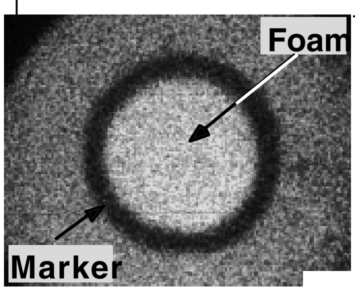
P.E. Dimotakis, J. Fluid Mech. 409, 69 (2000); Zhou et al., submitted, Phys. Rev. E (2002); Robey et al., Phys. Plasmas, in press

Measurements of turbulent instability growth have been performed in planar and convergent geometries

- Convergent experiments in cylindrical geometry







Planar geometry:

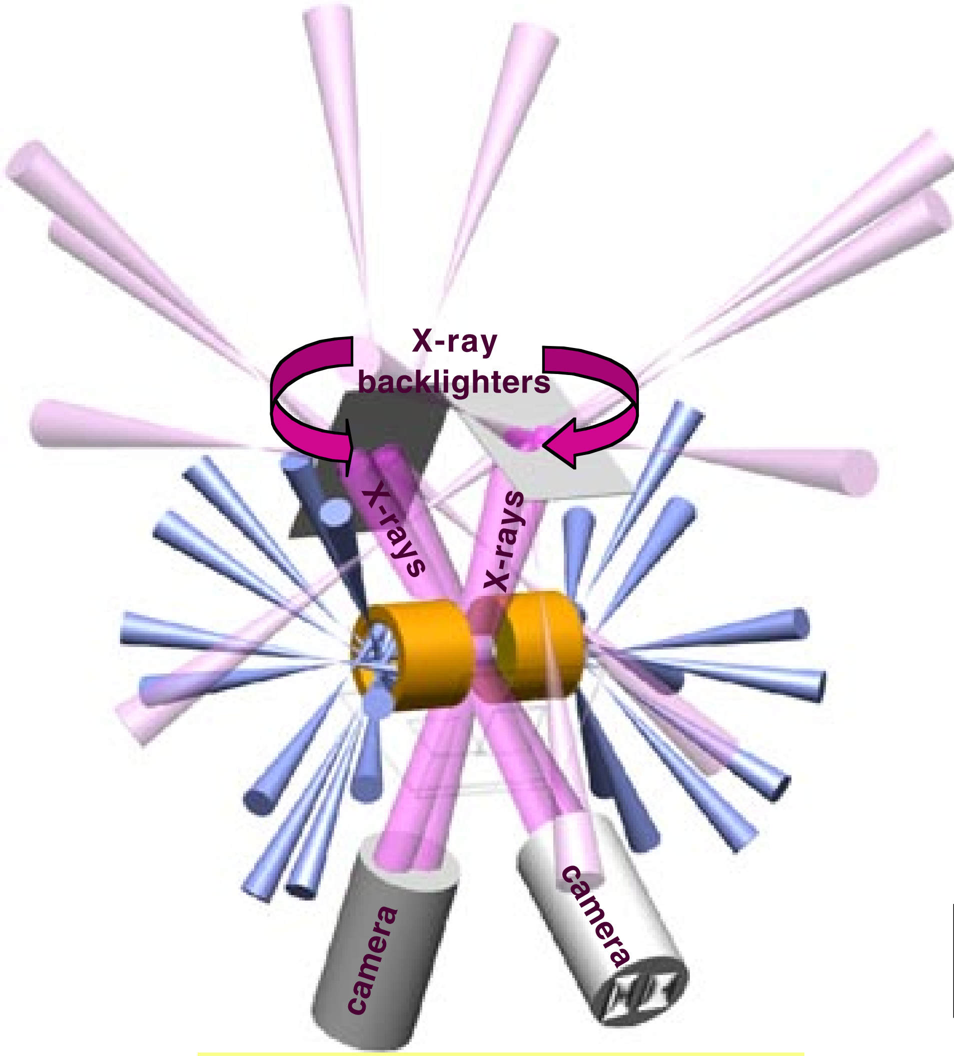
Turbulent RT, RM experiments: accuracy to 20 - 50% in model parameters

New facilities will allow higher accuracies and more detailed measurements of turbulent growth

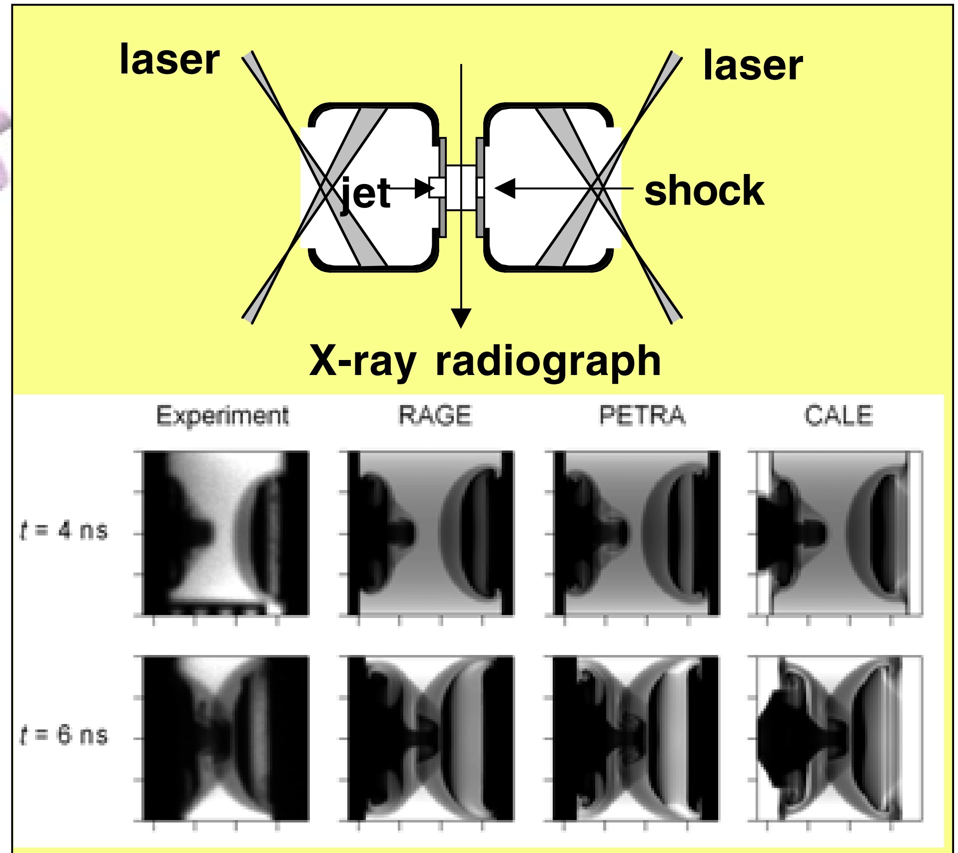
AWE — Los Alamos

N. E. Lanier *Submitted to PRL*, N. E. Lanier, *Submitted to Phys. Plas.,* Dimonte, Phys Plas, 6(1999); Edwards, Phys Plas, 7(2000)

These testbeds for large and mid-scale size hydrodynamics are well established



Radiographic images at different views in space and time

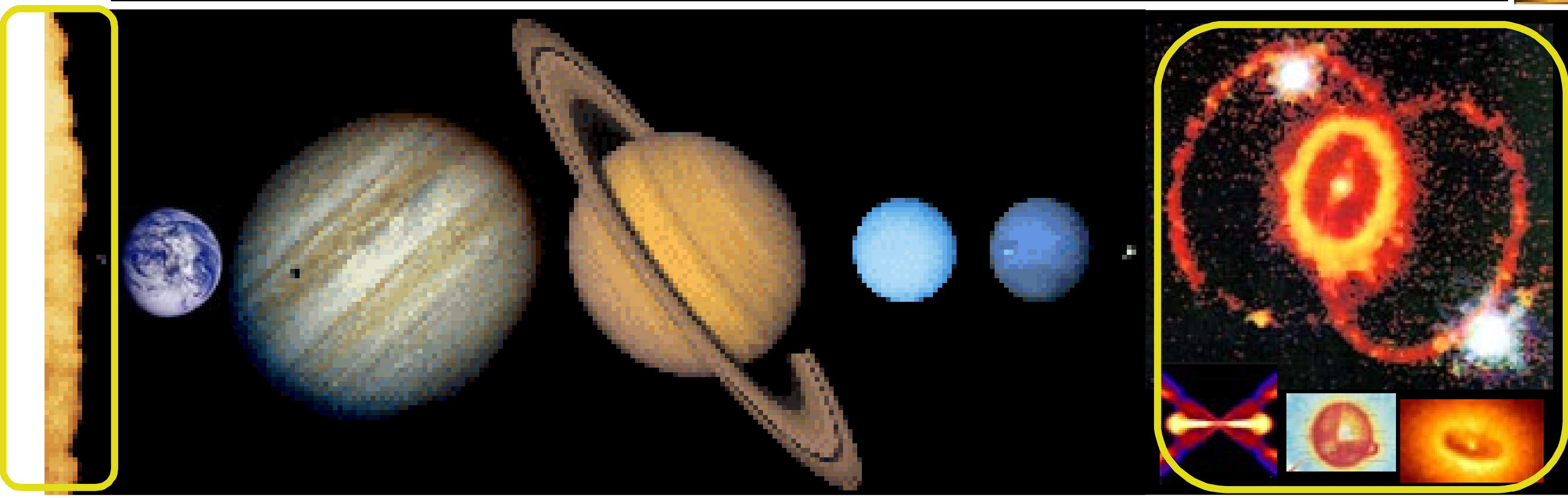


High Mach number supersonic jets were compared to codes

Experiments have started on Z, where target sizes are O(10x larger)

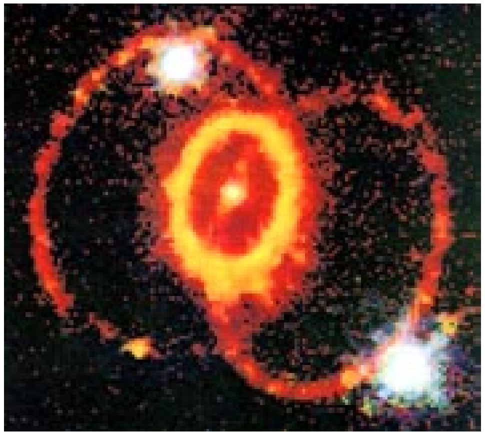
J. M. Foster, et. al,Phys Plas, 9 (5 PT2), 2251-2263 (2002).

Outline

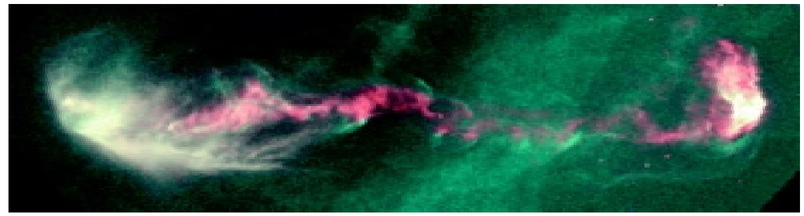


- **Significant advances in high energy density physics**
  - *Hugoniot equation-of-state*
  - *Materials science at high pressure*
  - *Hydrodynamics*
  - *Radiation transport and atomic physics*
- **Future directions**

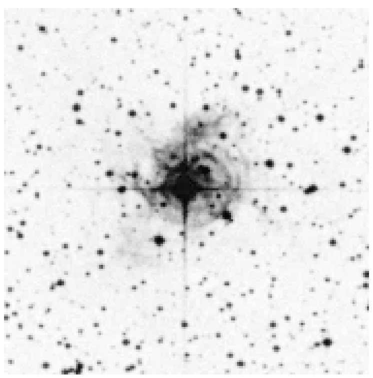
Interaction of of intense soft X-rays with matter is important in a host of astrophysical phenomena



Radiation penetration from a supernova into interstellar medium - ionization fronts



Formation of astrophysical jets - radiative cooling



Cepheid variables -
opacities of stellar envelopes

Radiation from accretion material in X-ray binaries - photoionized plasmas

Radiation

When is radiation important at high energy density conditions?

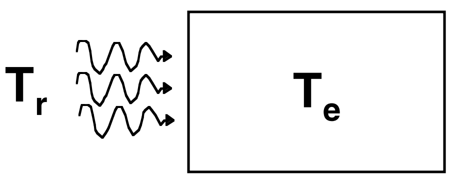
Local Energy Density:

Radiation energy density $\sim \dfrac{4\sigma T_R^4}{c}$ 1 Mbar => $T_R = 300$ eV

But material energy dominates $\dfrac{\text{Radiation Energy Density}}{\text{Material Energy Density}} \sim \dfrac{T^3}{\rho\,(Z/A)}$

At $T_R = 300$ eV, 1g/cc => $\sim 10^{-3}$ Or T~2 keV

Energy Transport:

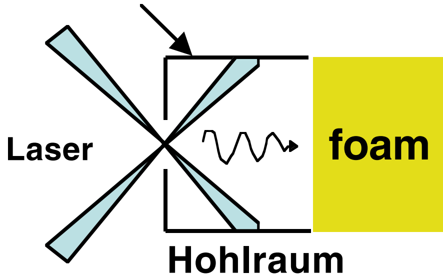


$$\frac{\text{Radiation Energy Flux}}{\text{Material Energy Flux}} = \frac{\text{Radiation Energy Density}}{\text{Material Energy Density}} \frac{c}{v}$$

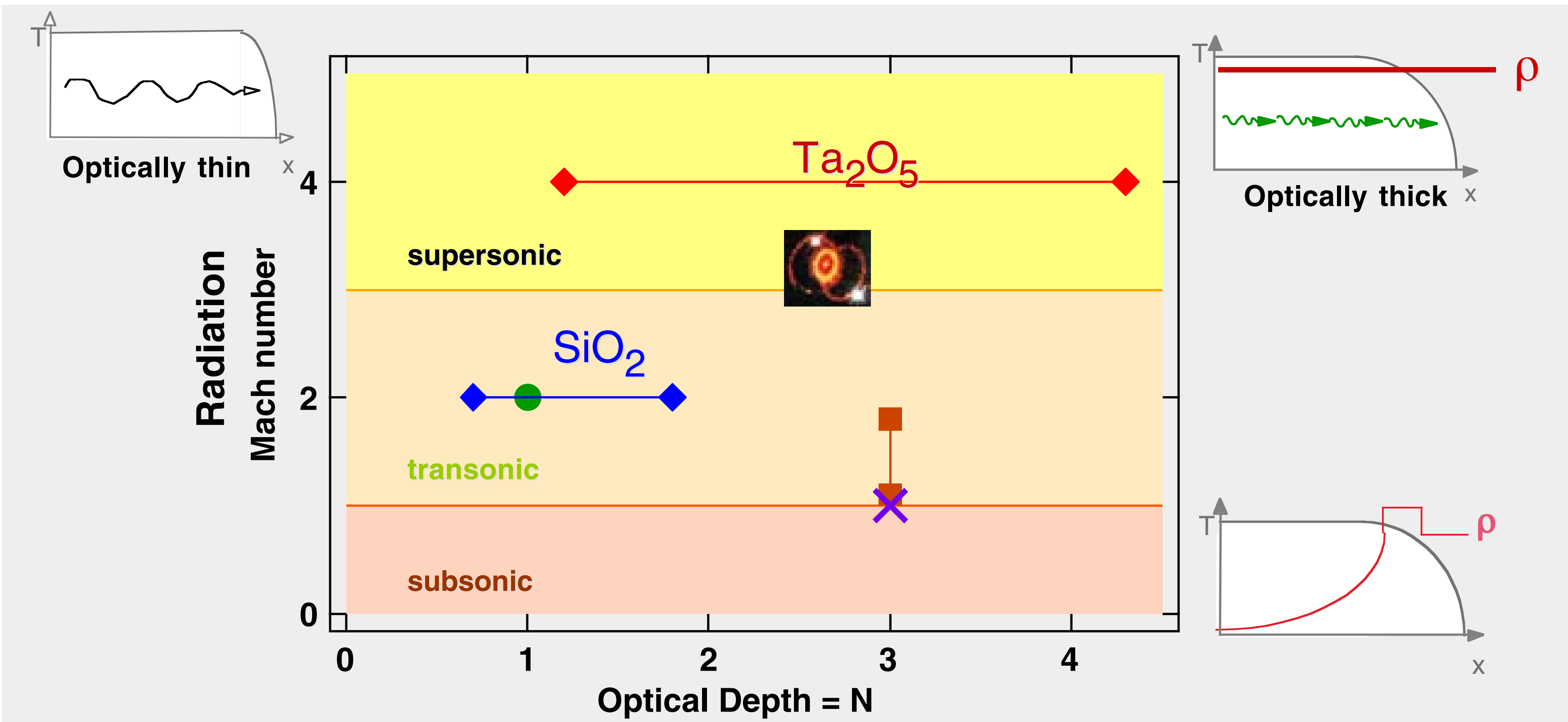
Important in most stellar atmospheres: sun $\sim 5 \times 10^4$

At T = 300 eV, 1g/cc, v = sound speed => ~ 2

Supersonic ionization fronts have been created in the laboratory



$$\frac{\textbf{Radiative energy flux}}{\textbf{Material energy flux}} = \frac{\sigma T^4}{\varepsilon \rho c_s} \propto \left(\frac{x}{mfp_R}\right)\left(\frac{x}{c_s}\right) = NM$$



Back, C. A., et al. (2000). Physics of Plasmas **7**(5 PT2): 2126-2134.

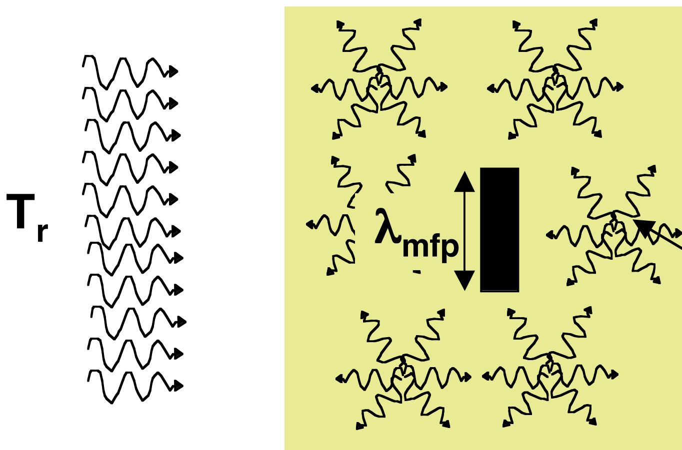
Afsharrad, T., (1994). Physical Review Letters **73**(1): 74-77.
Hoarty, D., et al. (1999). Physics of Plasmas **6**(5 PT2): 2171-2177.

Massen, J., (1994). Physical Review E **50**(6): 5130-5133.

X Bozier, J.C. et. al., (1986) Phys Rev Lett, 57: 1304.

Several techniques are available to solve radiation transport problems

- **Diffusion** assumes radiation ~ isotropic

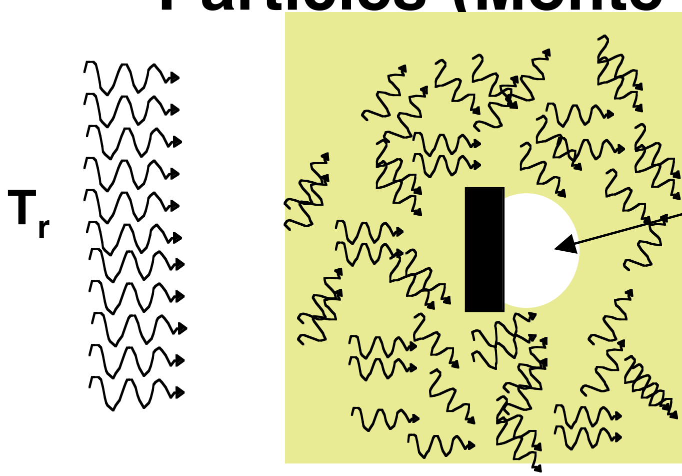


requires large optical depth
e.g deep inside stars

Radiation from a far away Supernova illuminating a protostar is non-isotropic

Radiation transports behind a wall

- **Particles (Monte Carlo)**



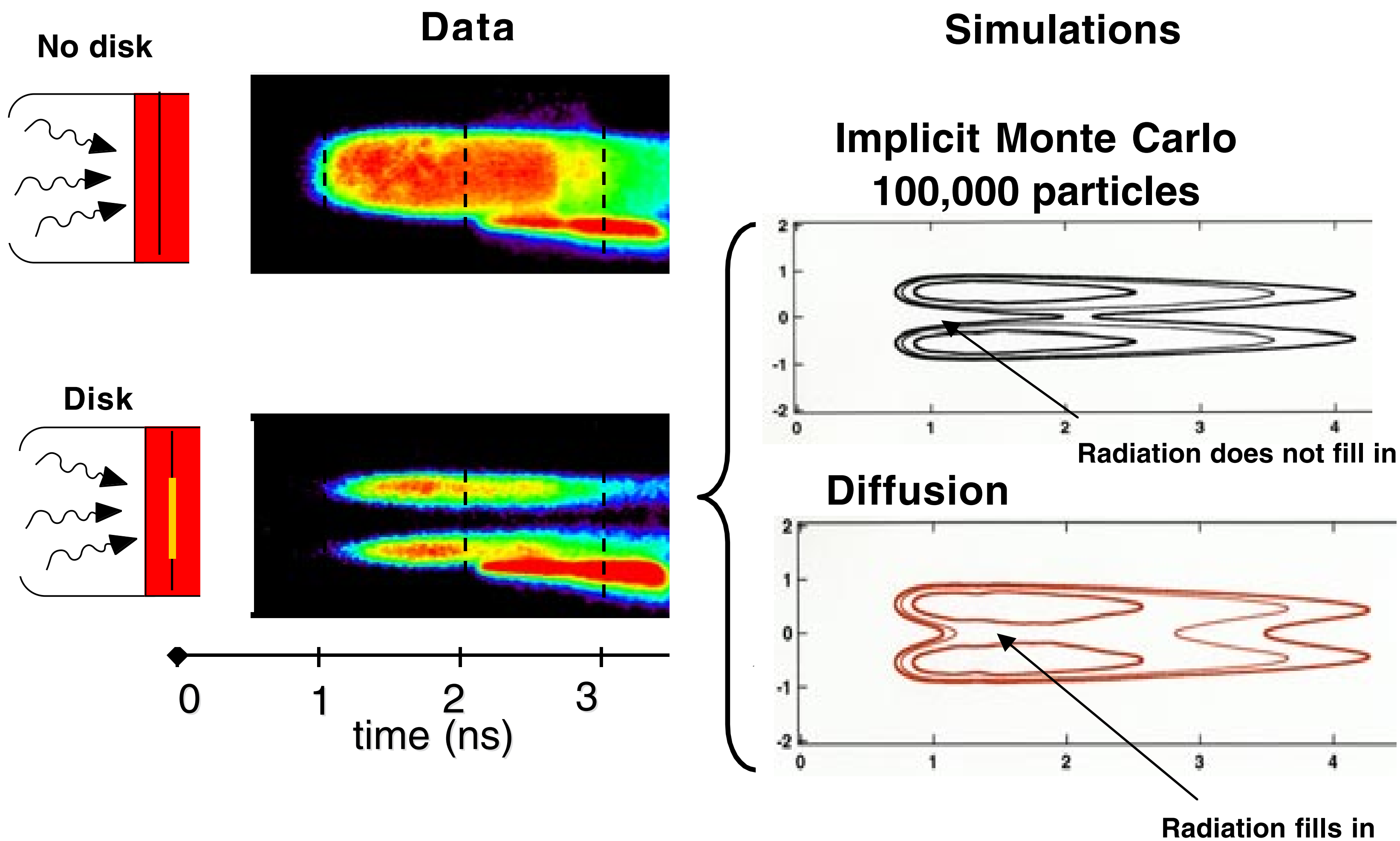
Photons are tracked as particles

Radiation does not transport behind a wall

Signal/Noise ~ (# of particles/cell)$^{1/2}$
=> big computers

Radiation

Data from experiments can now quantitatively evaluate radiation transport methods



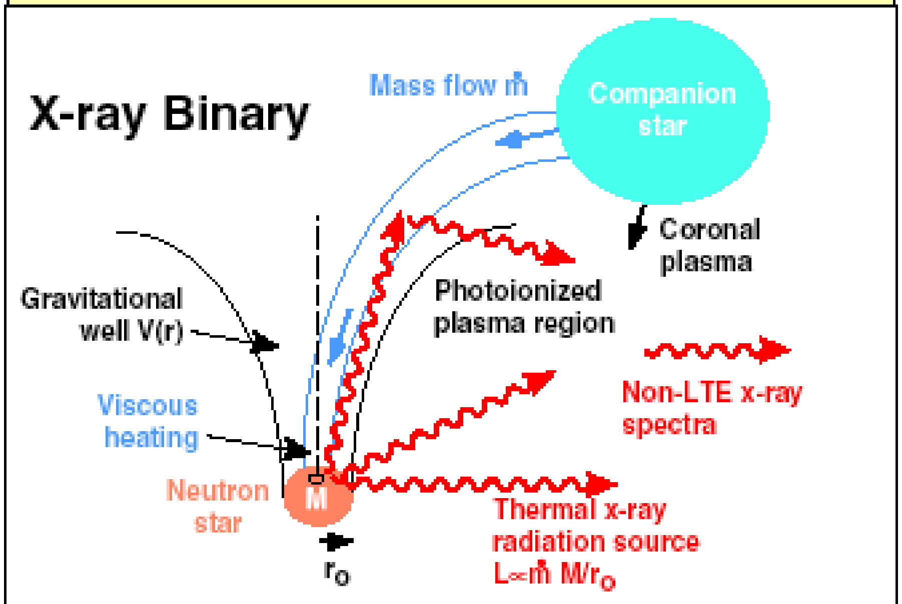
Advanced radiation transport algorithms like Implicit Monte Carlo agrees better than diffusion in Omega experiments

C. A. Back, to be submitted to Phys. Plas.

Radiation

X-ray astrophysics now needs a detailed understanding of photoionized plasmas

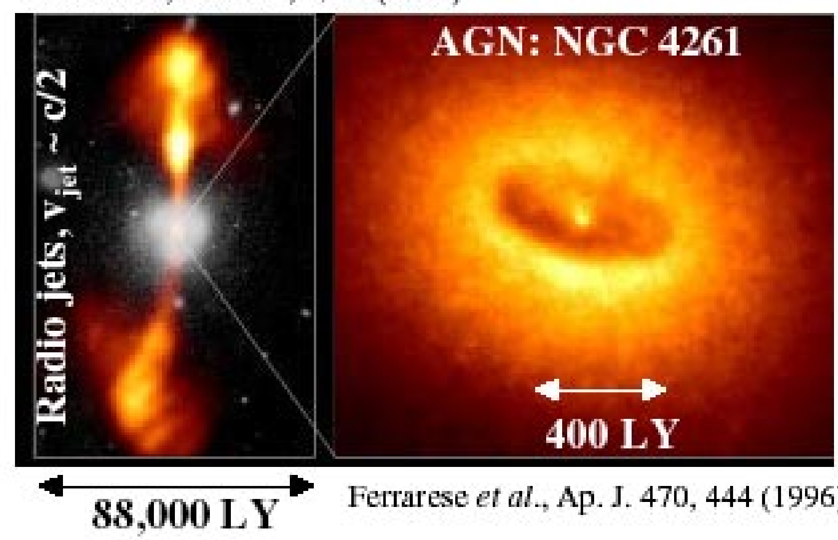
Gravitational energy of infalling matter ⇒ X-rays



Half of all X-ray sources are accretion-powered:
- Active Galactic Nuclei (AGNs)
- Cataclysmic Variables (CVs)
- Black Hole or Neutron Star X-ray Binaries

Copious X-rays photoionize the accretion disk

Piner *et al.*, A.J. 122, 2954 (2001)



Ferrarese *et al.*, Ap. J. 470, 444 (1996)

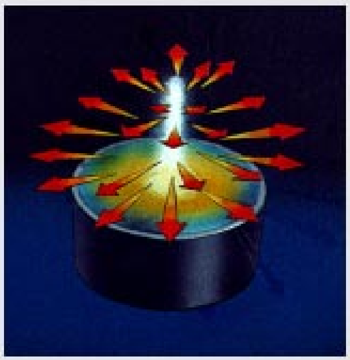
High radiation fields, low density so 3 body recombination

$\xi \sim 4\pi I/n$ ~Irradiance/electron density

$\xi \gg 1$ for regimes of interest

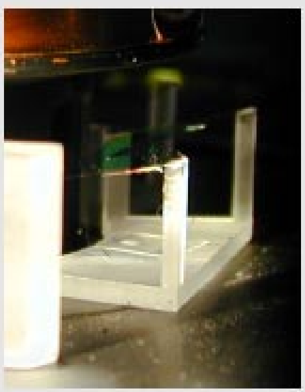
Radiation

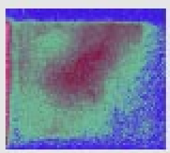
Understanding atomic physics in photoionized plasmas allows intrepretation of astrophysical spectra



Z is Radiation Source

80 TW, 160 eV
Quasi-blackbody w/tail
Cylinder 1.0 cm high,
0.15-0.2 cm diameter

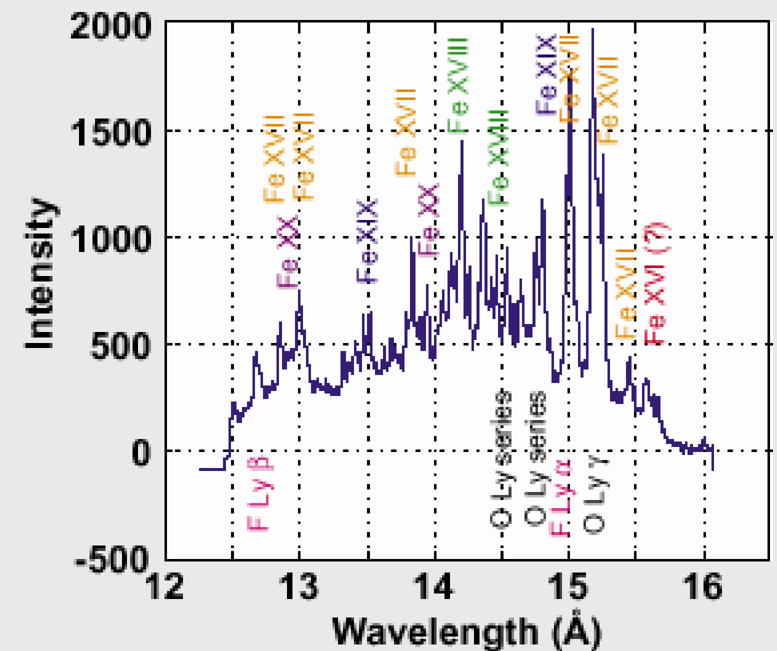




Photoionized Sample

1.6 cm from center of source
3 Fe : 2 NaF mixture
$n_{Fe} = 8 \times 10^{17}$ / cm^3
n_e 29 n_{Fe} 2.5×10^{19} / cm^3

Emission Spectrum of a Plasma at Conditions of a Photoionized Accretion Disk



RSI 72, 1227 (2001)

The first experimental benchmark for X-ray photoionized plasma models is available, ζ ~ 20

Te = 30 eV

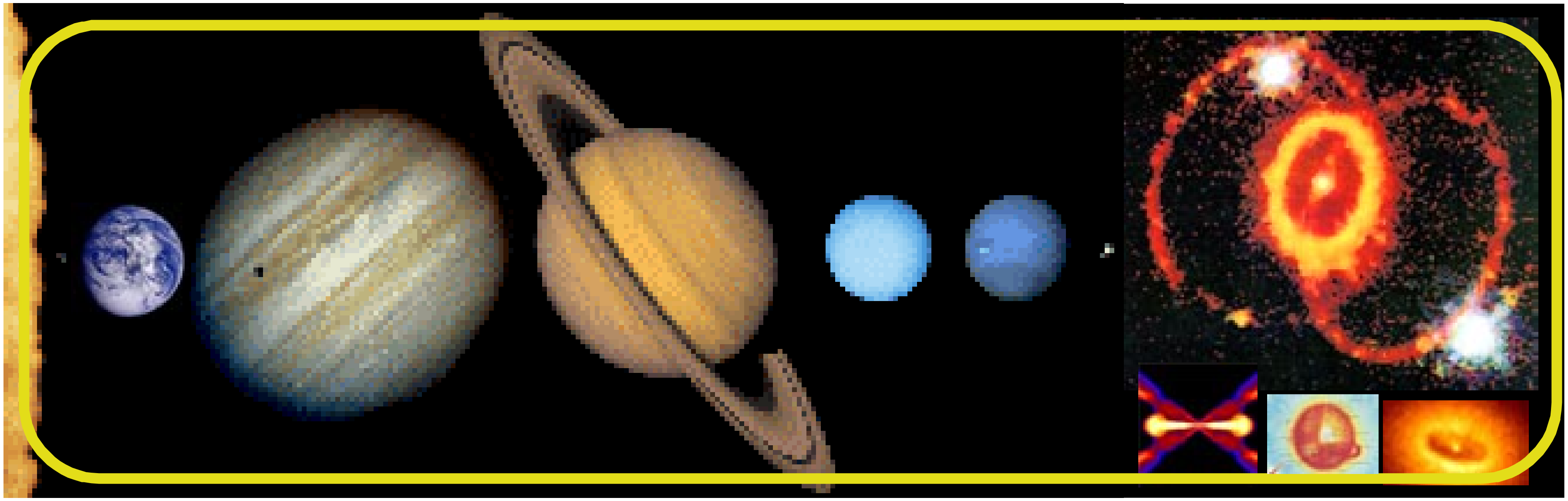
Z = 16.5 ± .5 in comparison with 6 models

Universities worldwide are engaged in research in high energy density physics

University	Research area
Berkeley	Precompressed EOS, X-ray diffraction
UCSD	Materials dynamics
U of Michigan	Supernova remnants, radiation transport
Cornell	High density plasmas
Univ of Rochester	Astrophysical jets, EOS
U of Colorado	X-ray interferometry, laboratory astrophysics
U of Reno	Z-pinch plasmas
U of Arizona	Laboratory astrophysics
Rice University	Radiative blast waves
U of Maryland	Laboratory astrophysics
UC Davis	Radiative blast waves
MIT	Nuclear physics
George Mason	Supernova hydrodynamics
U of Texas	Material Dynamics
U of Wisconsin	Atomic physics

University	Research area
Ecole Polytechnique	Opacity, EOS of water
Univ of British Columbia	EOS of foams
Osaka University	Laboratory astrophysics
Imperial College	Radiation transport, Z-pinches
University of Milan-Biocca	EOS of Au
Univ of Essex	EOS of foams
Oxford University	Material Dynamics
Univ Milan	EOS water, foams

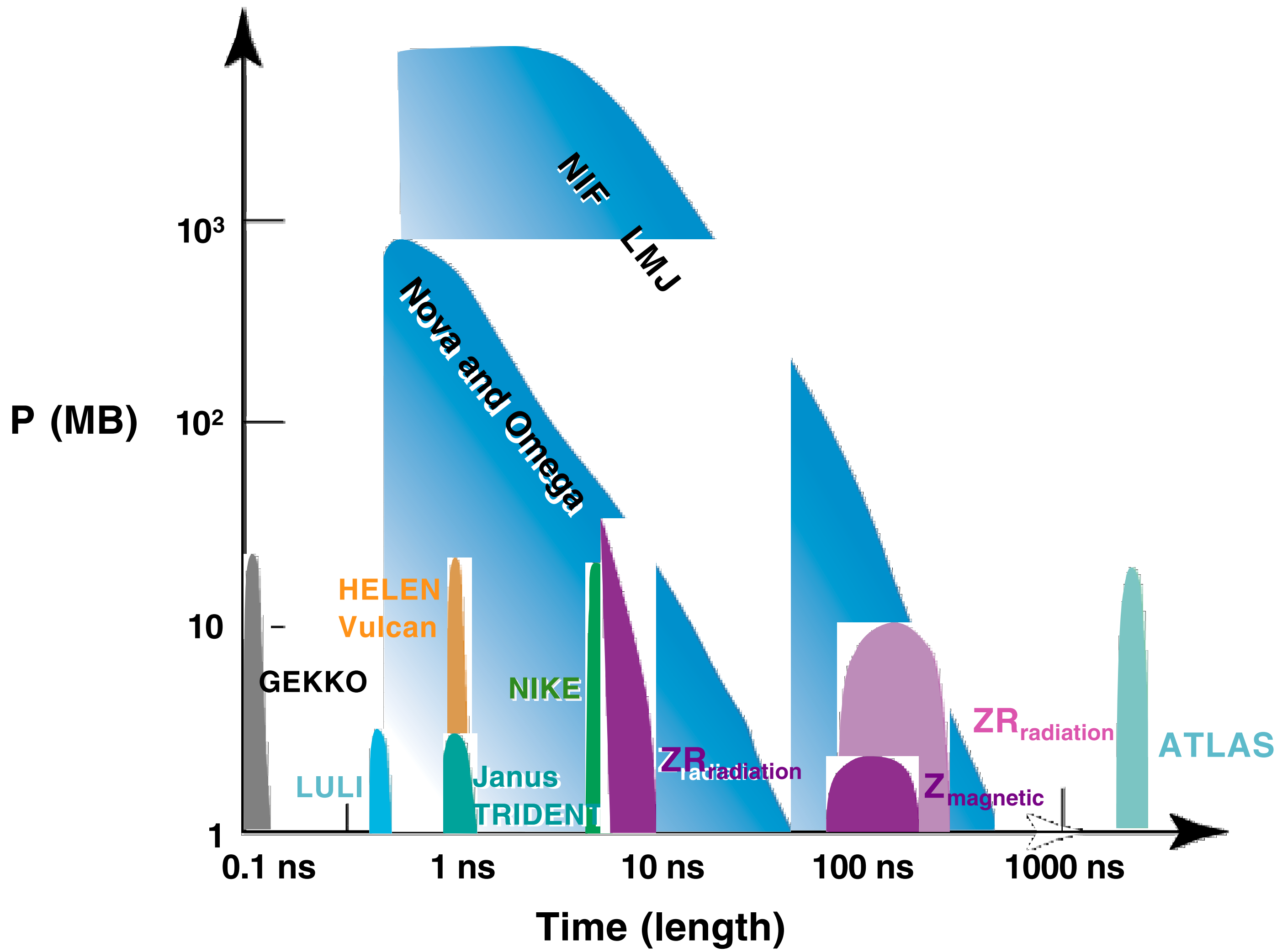
Outline



- **Significant advances in high energy density physics**
  - *Hugoniot equation-of-state*
  - *Materials science at high pressure*
  - *Hydrodynamics*
  - *Radiation transport and atomic physics*
- **Future directions**

Future

New facilities will expand high energy density research



Future

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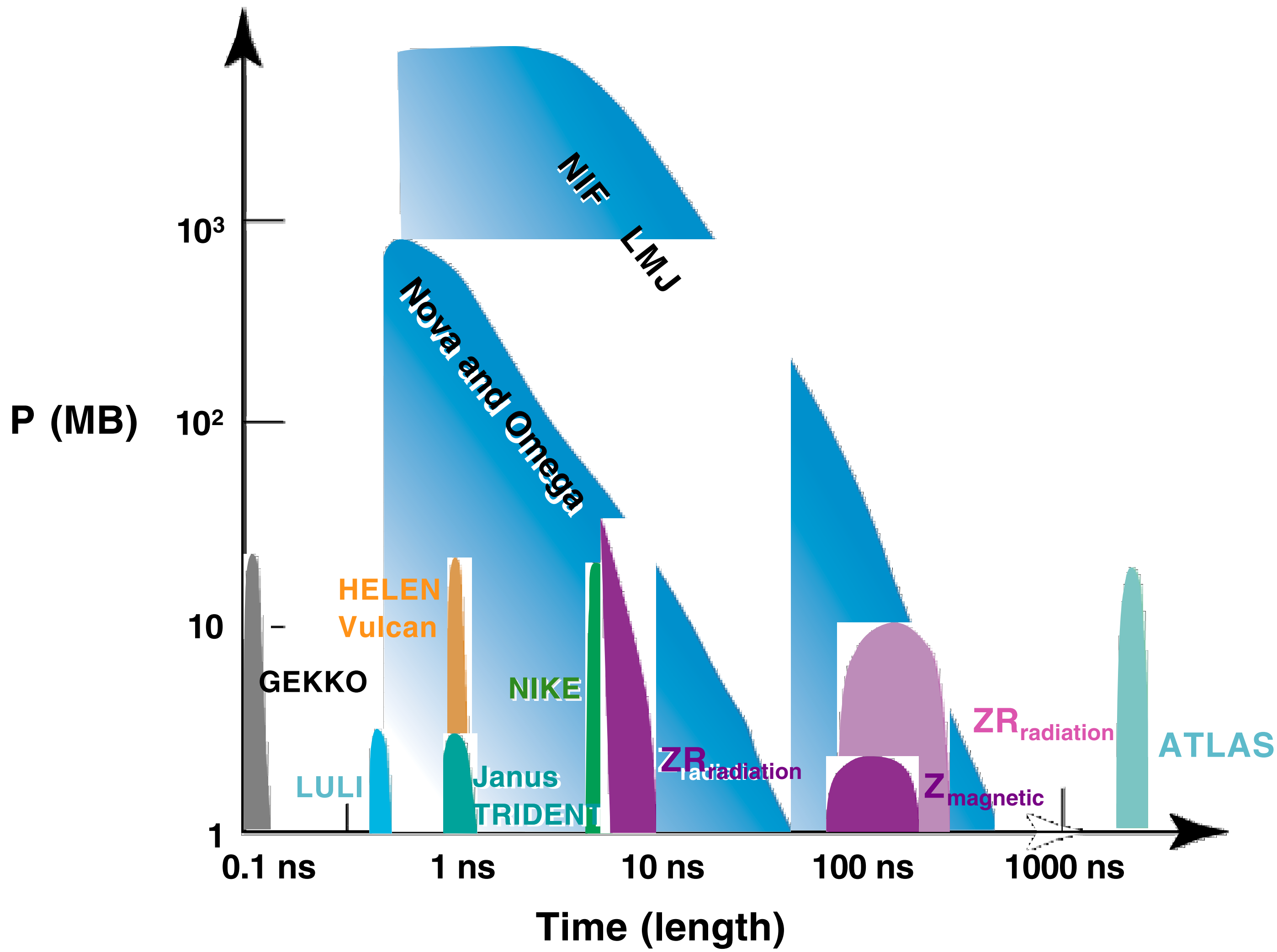

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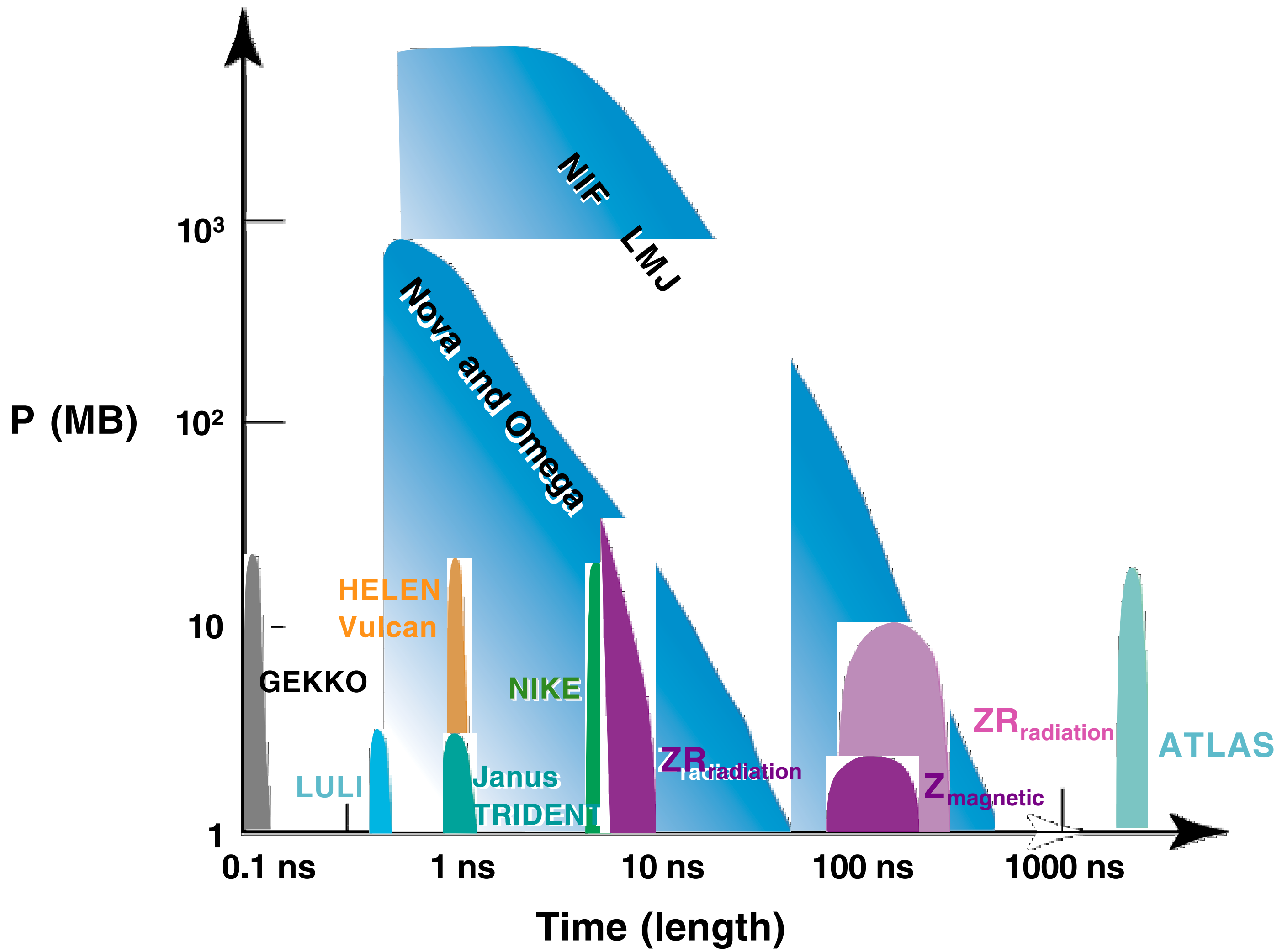

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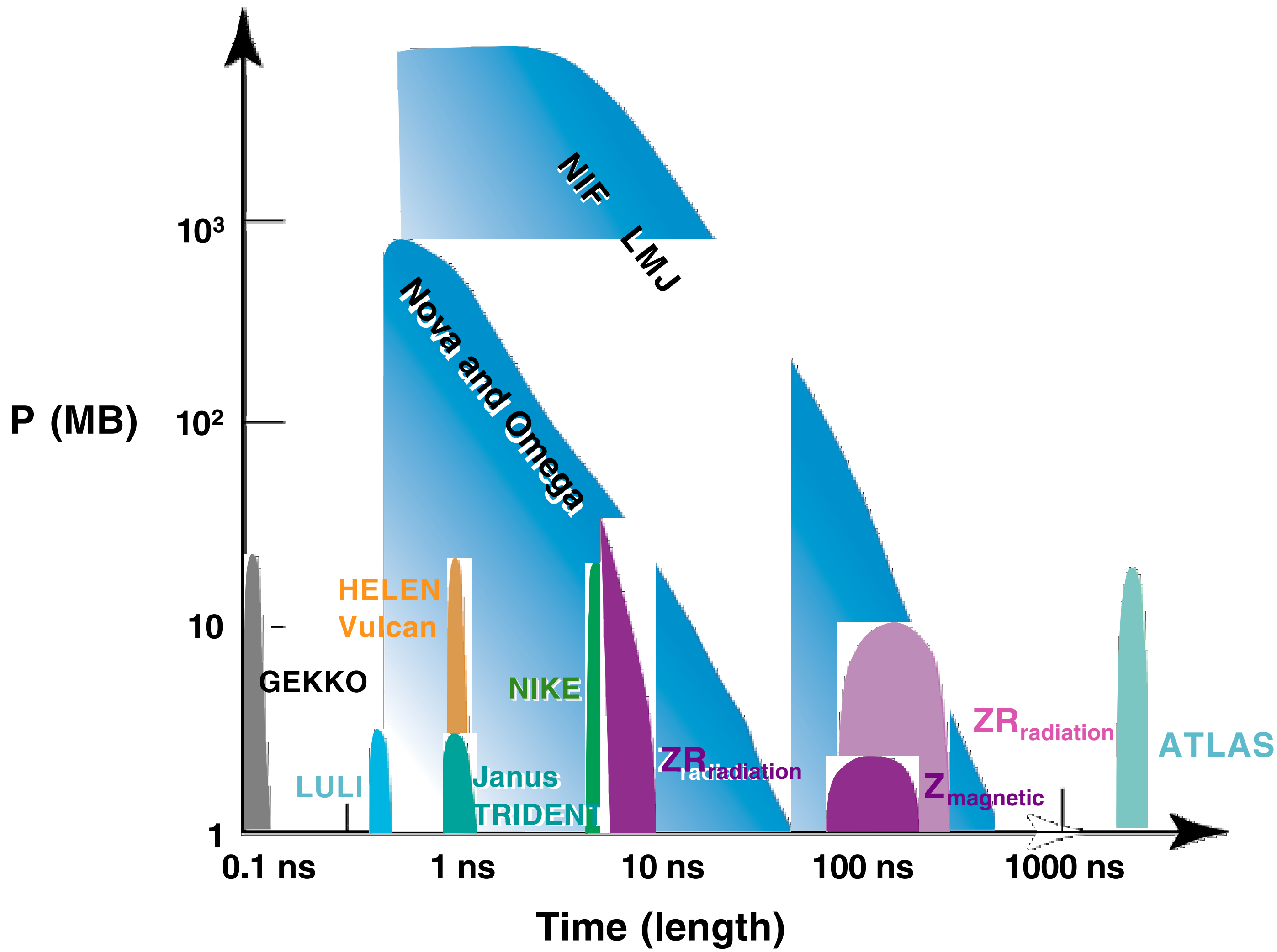

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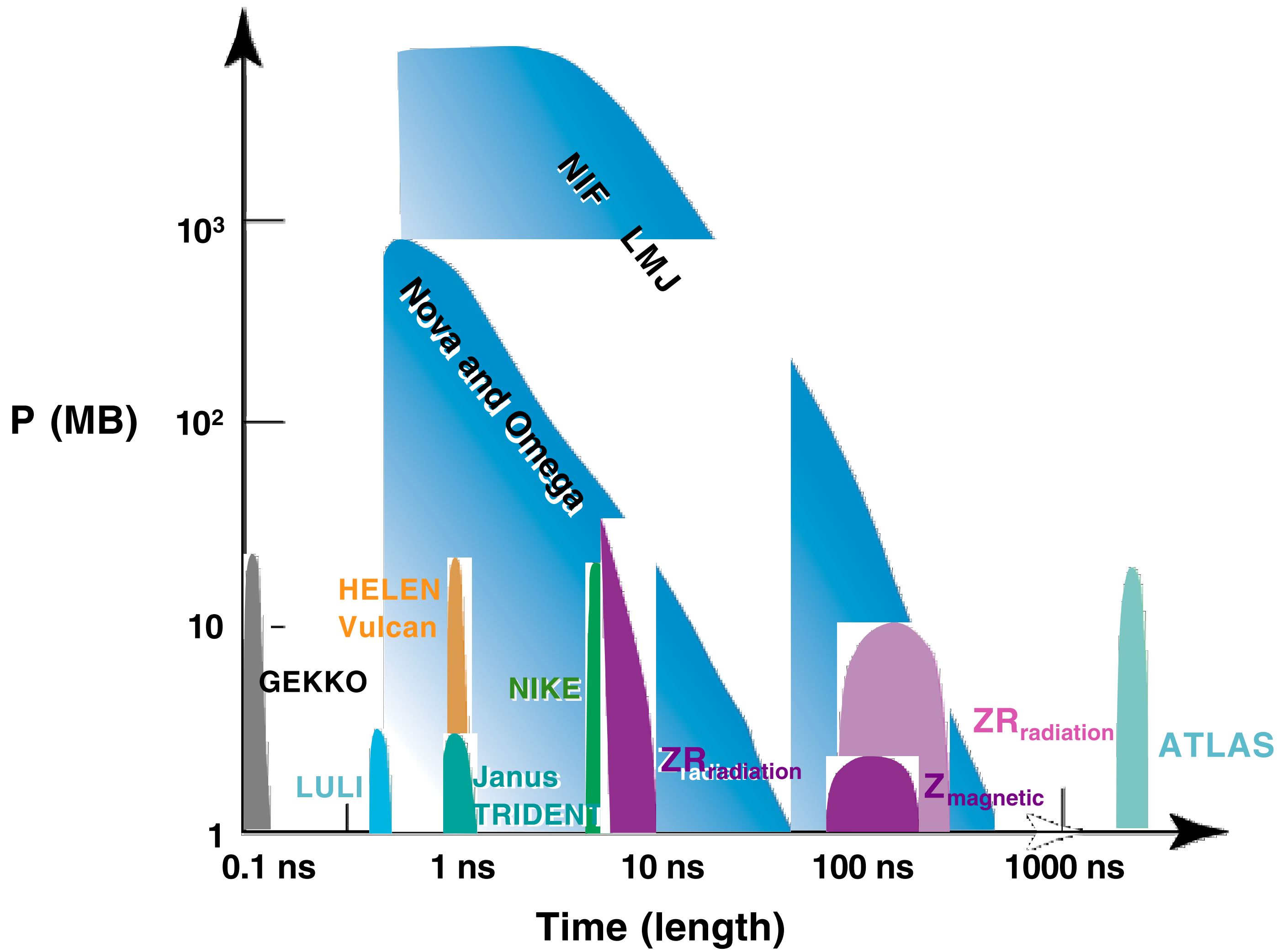

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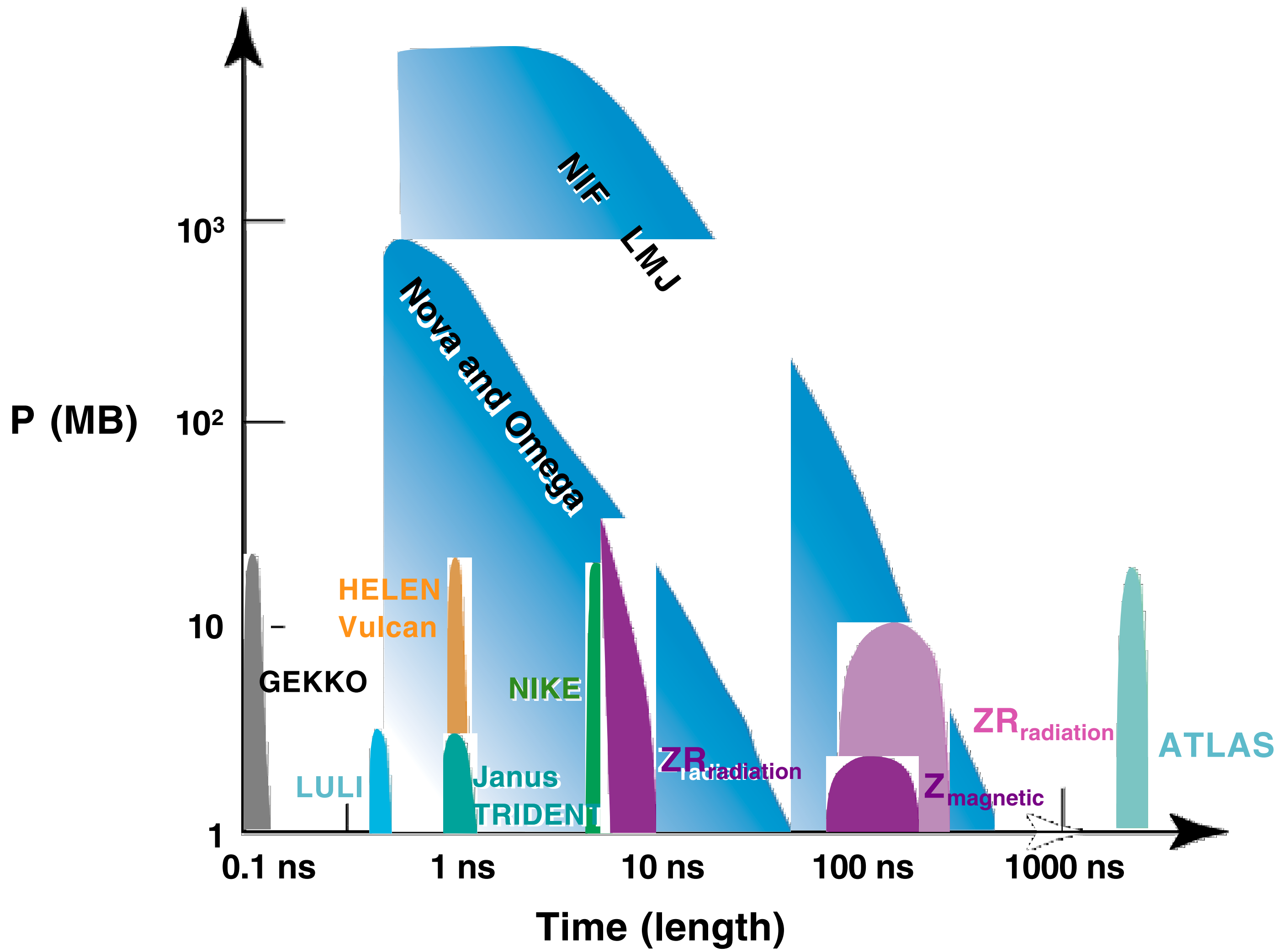

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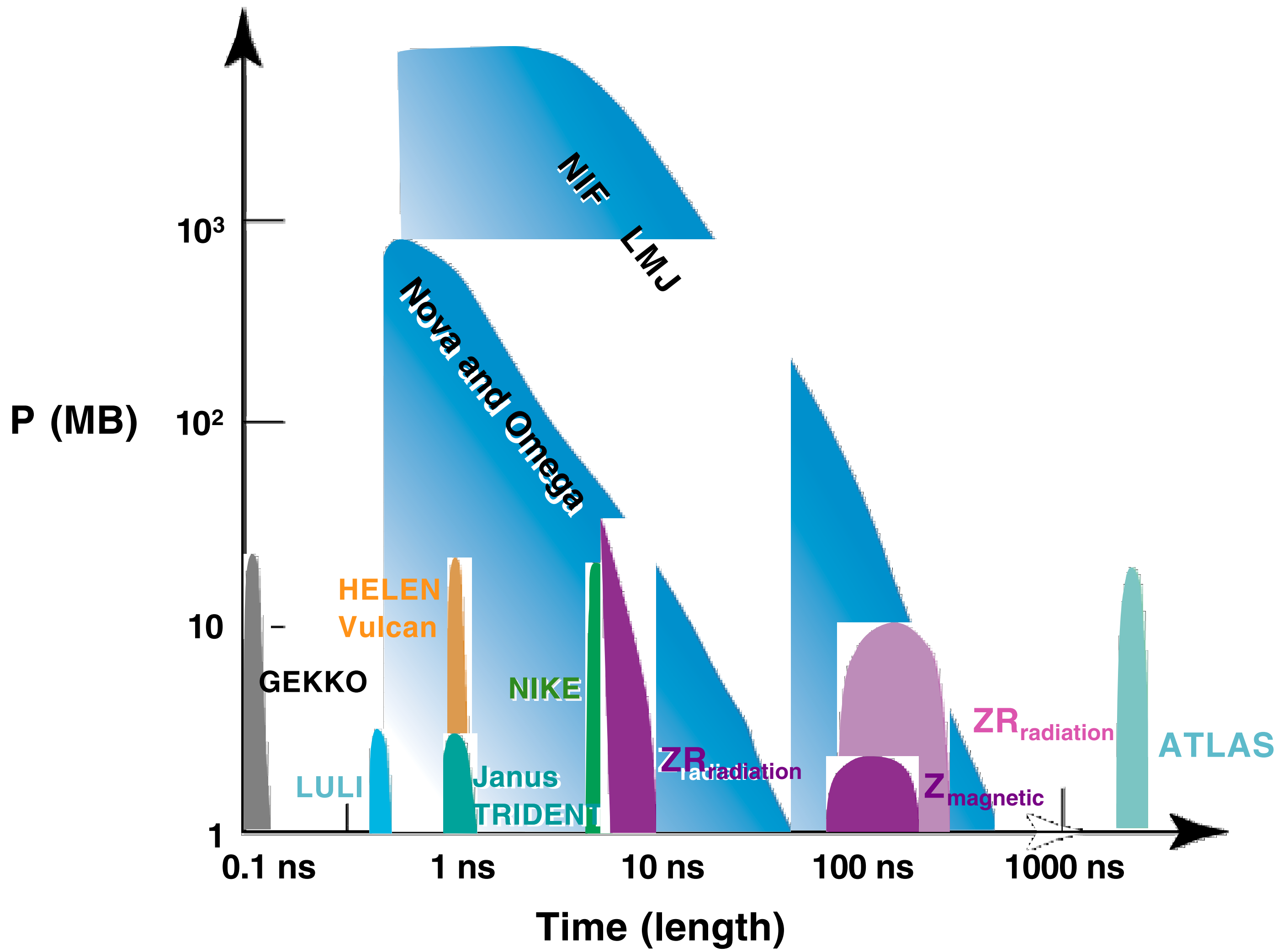
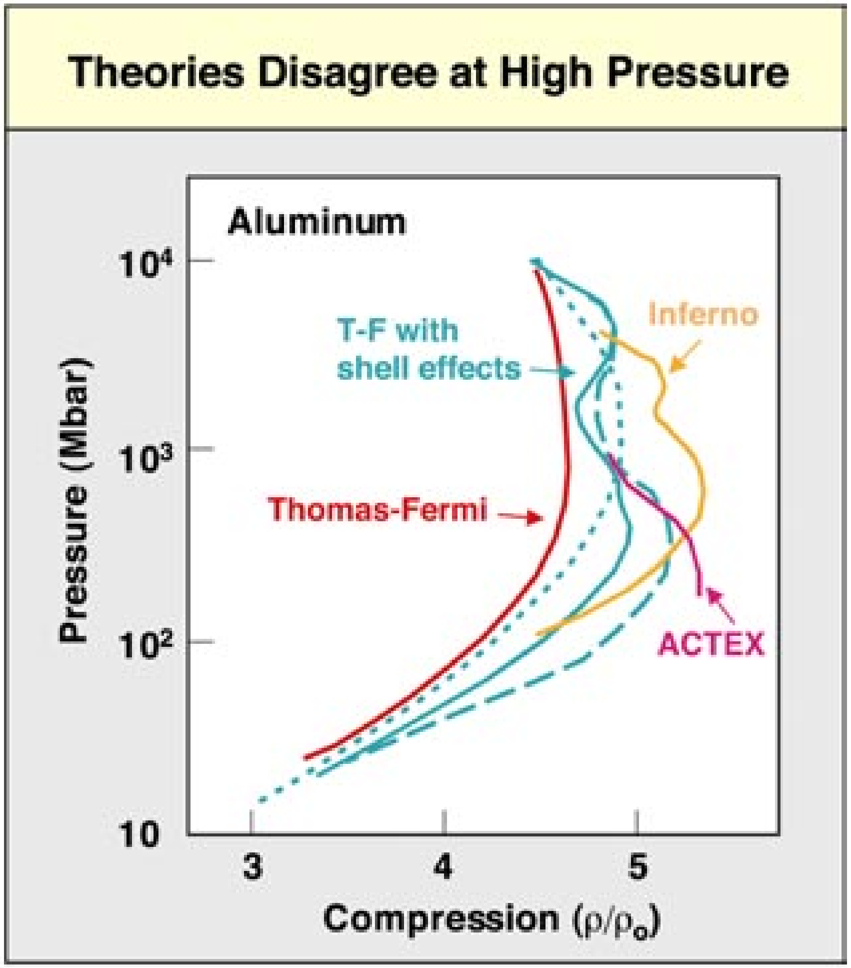
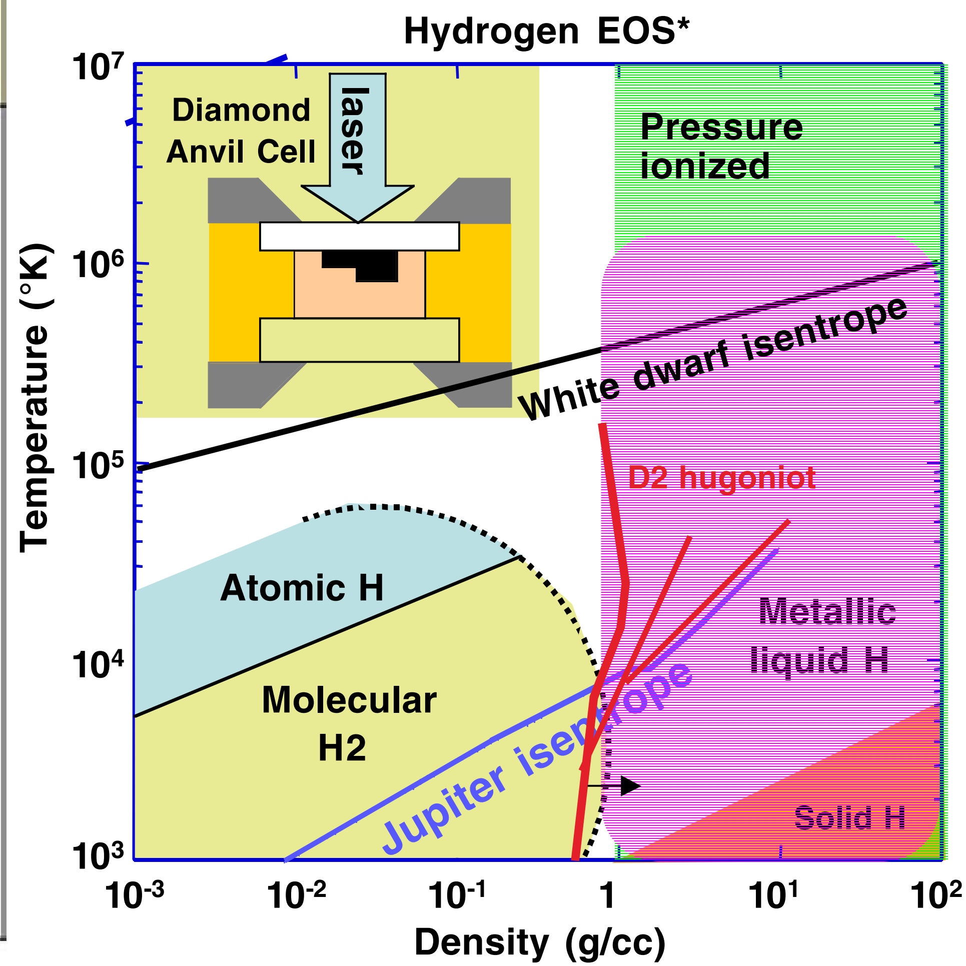


Future

Access to new regimes of EOS space will allow investigations of new physics





At high ~ Gbar Hugoniot pressures available on NIF, ionization of shells affects predictions

Multishocks, precompression or isentropic compression will access new regimes

Future

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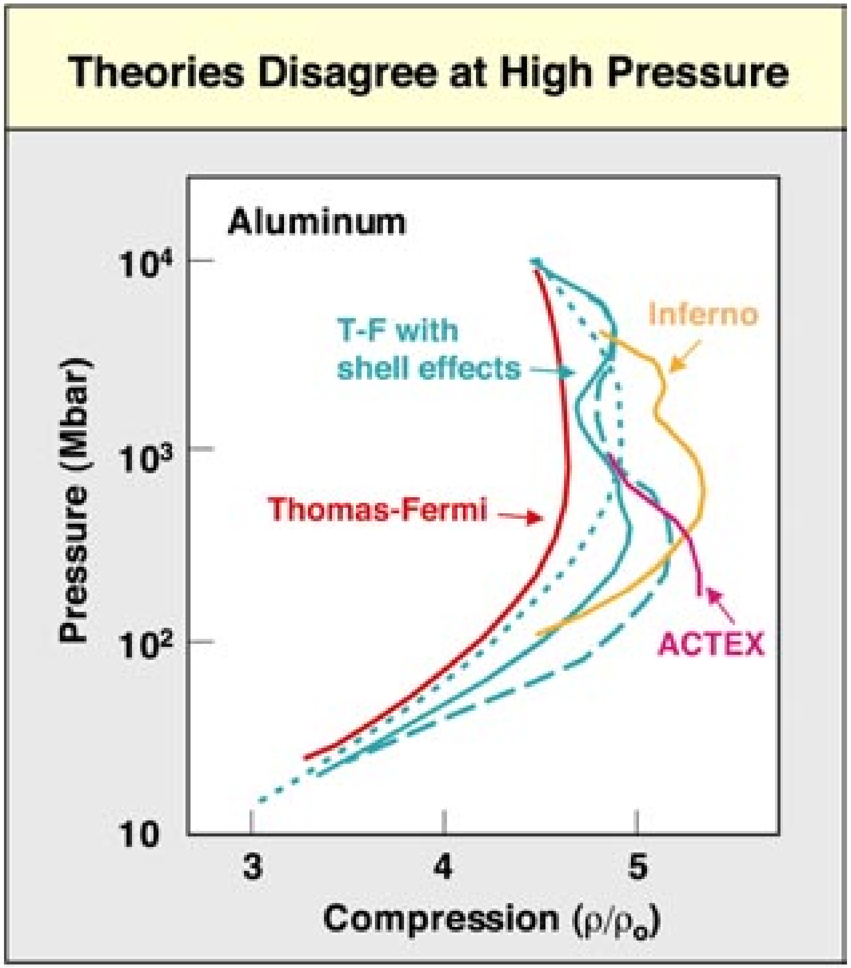

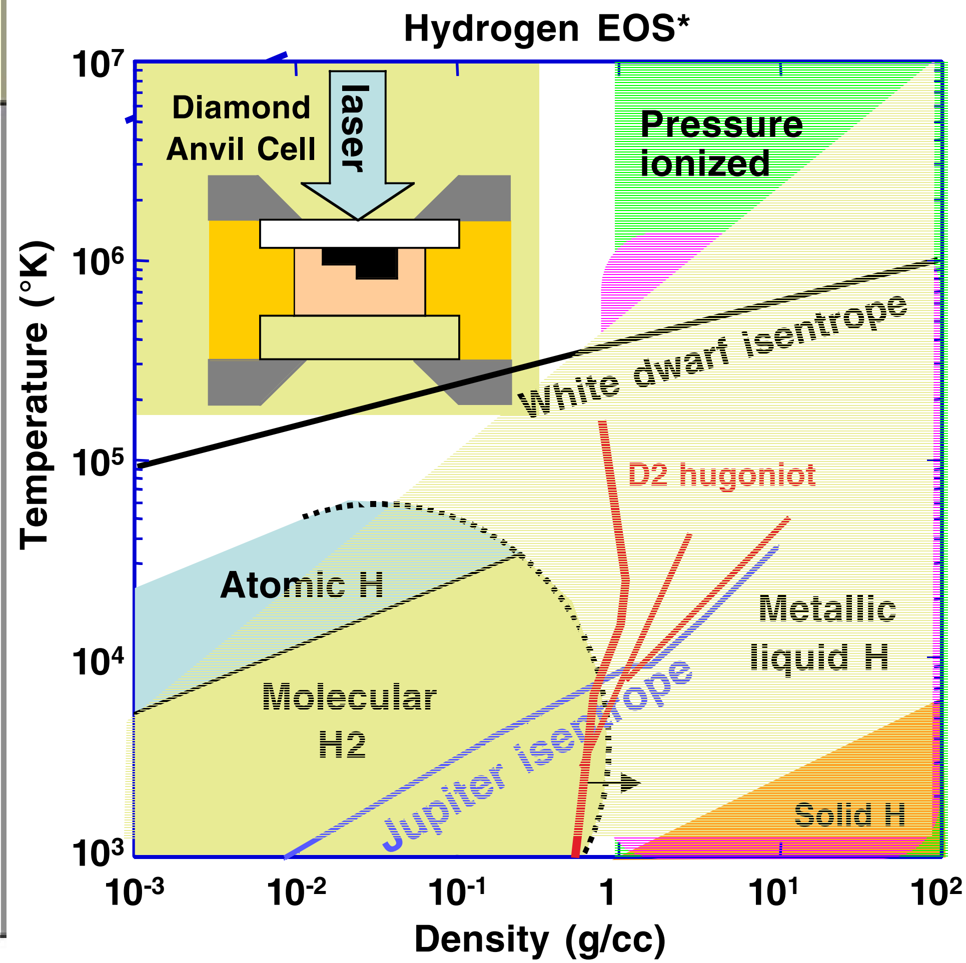

At high ~ Gbar Hugoniot pressures available on NIF, ionization of shells affects predictions

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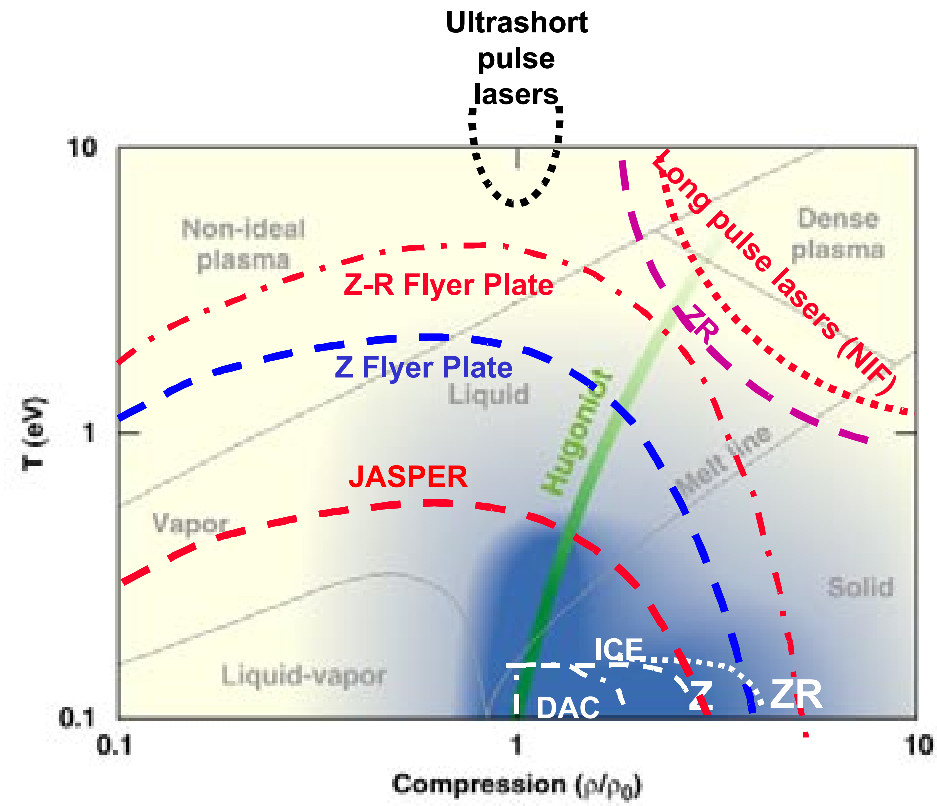
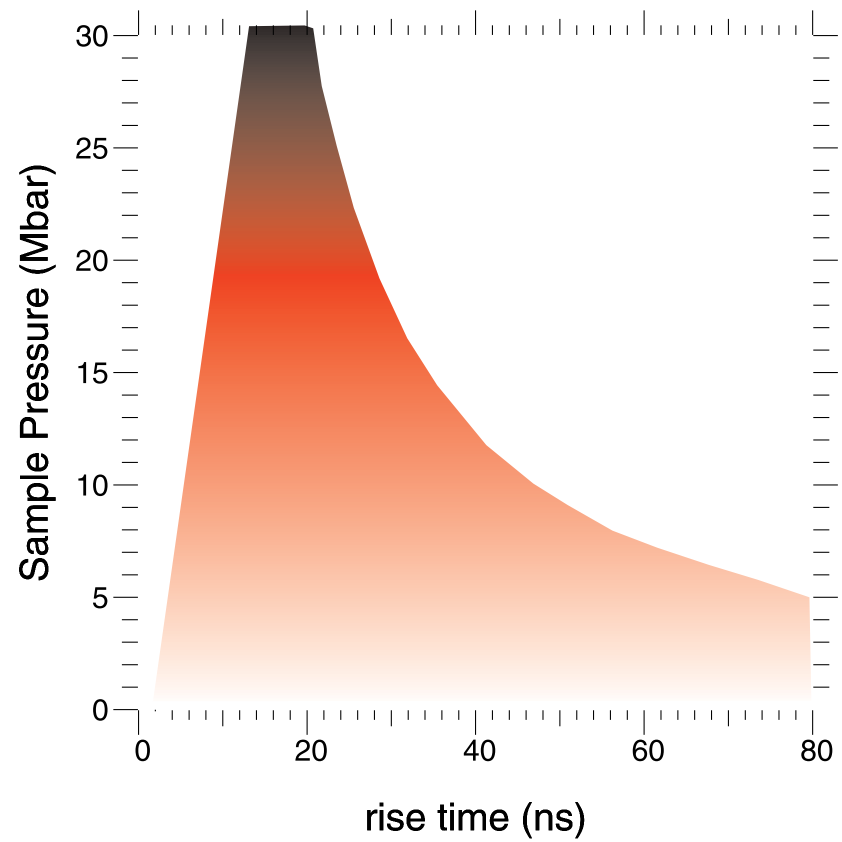
Future

Very high pressures will be able to be accessed isentropically for materials science studies





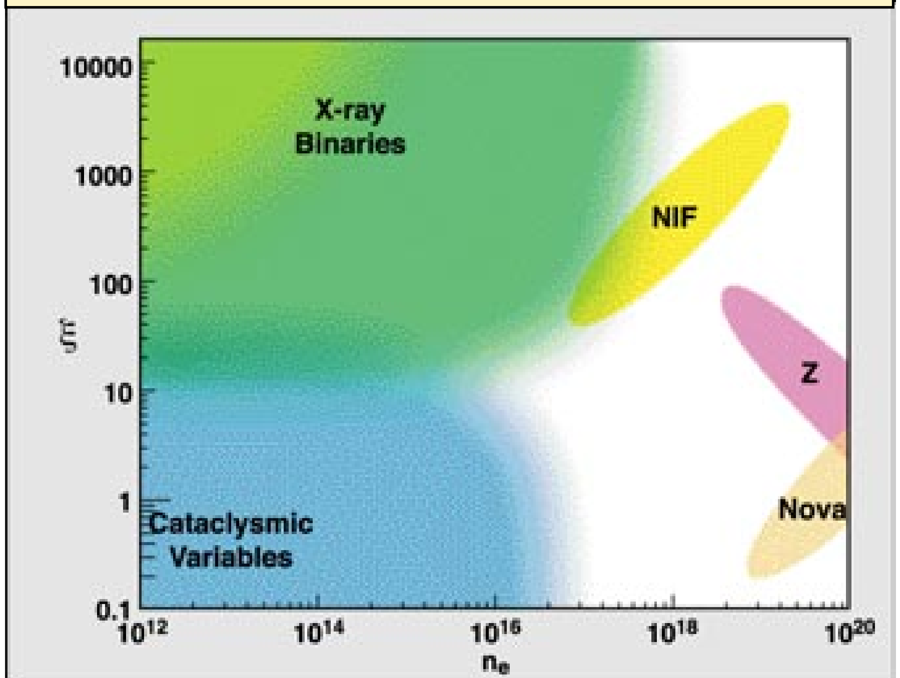
- Isentropic pressures exceeding 10 Mbar for condensed matter studies on ZR
- Flyer plate impact pressures of several tens of Mbar for precise Hugoniot experiments

NIF will reach > 20 MBars and measure strain rate and grain size effects

Future

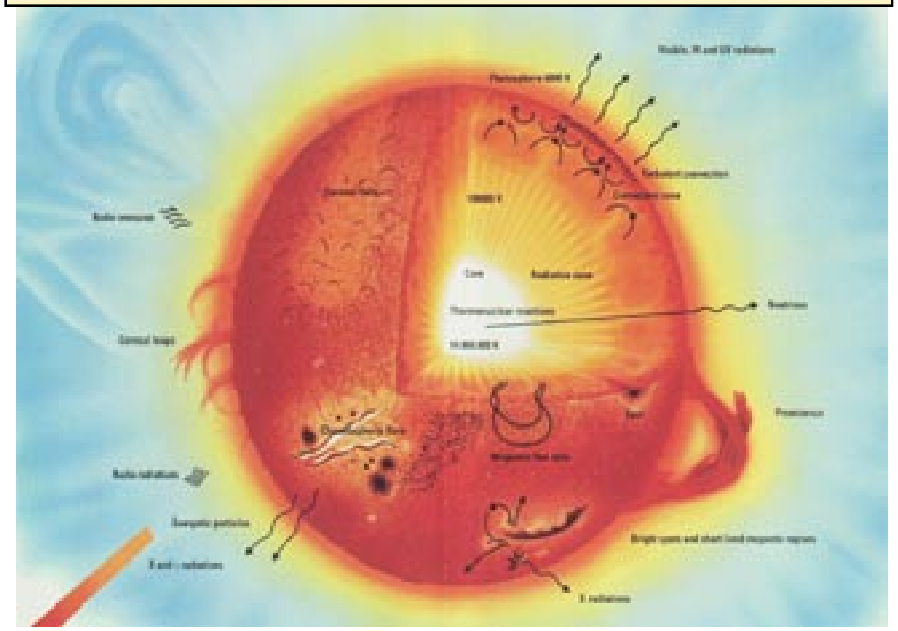
New regimes will allow measurements closer to astrophysical conditions

Photo-ionized Nebulae



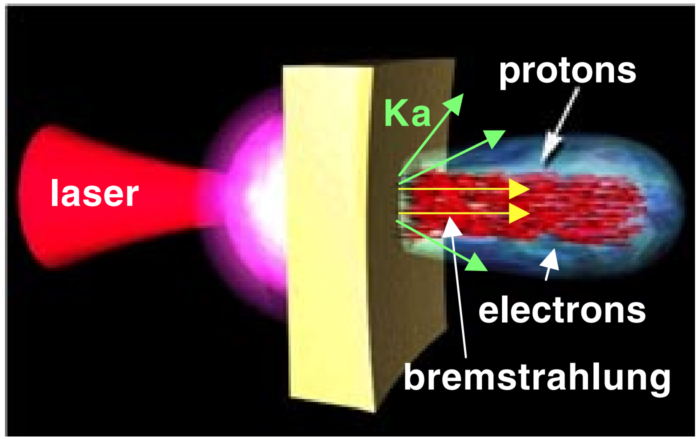
NIF & LMJ extends experiments closer to X-ray binary conditions

Fe opacity impacts Solar models



NIF and LMJ extends range of temperatures for opacity measurements to > 300 eV

New class of petawatt lasers have potential for accessing and probing high energy density conditions



Hot electrons, protons, Ka, MeV bremstrahlung are generated

- High intensity electric and magnetic fields are generated

$$\frac{\varepsilon E^2}{2} = 1 \text{ Mbar}$$

E ~ 10^{11} W/cm^2 ~ e/r^2
electric field in Bohr atom

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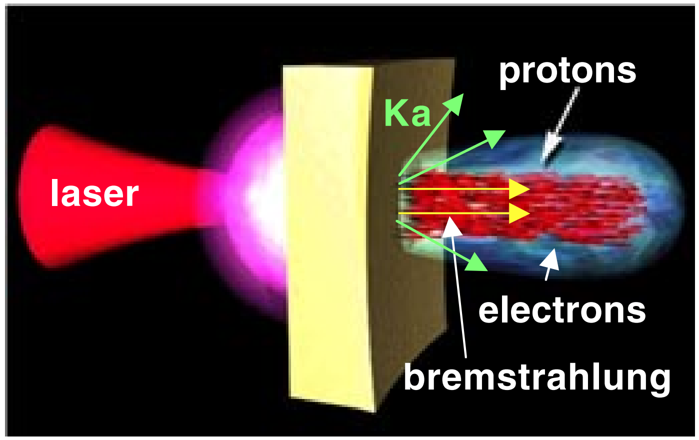

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I ~ 3 x10^{15} W/cm^2 $\longrightarrow$ Hot electrons ------> Ka X-rays

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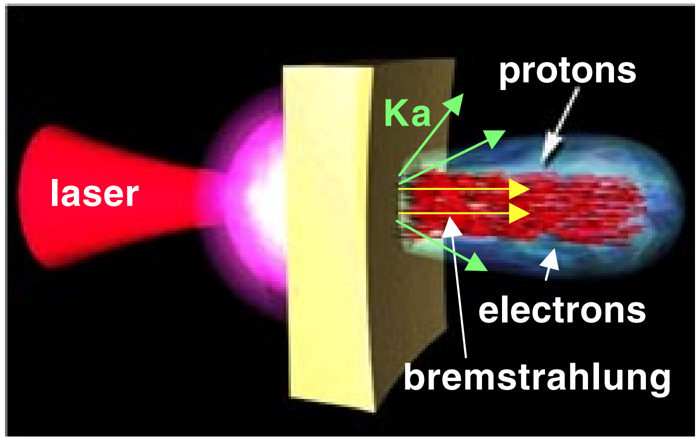

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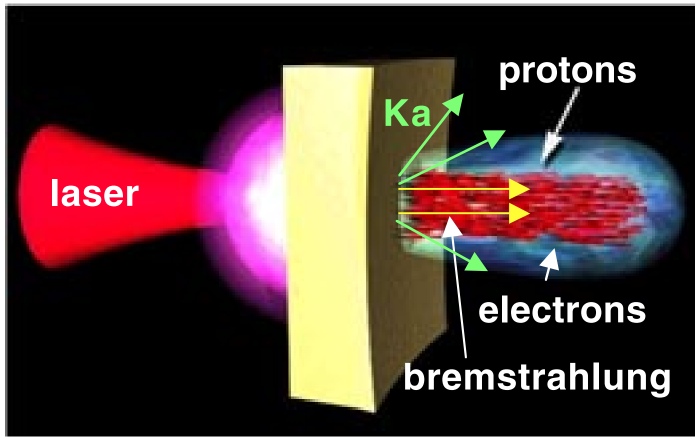
$E \sim 10^{11}$ W/cm^2 $\sim$ e/r^2
electric field in Bohr atom

$I \sim 3 \times 10^{15}$ W/cm^2 ⟶ Hot electrons ------> Ka X-rays

$I \sim 10^{18}$ W/cm^2 ⟶ $\dfrac{\text{quiver momentum}}{m_e c} = 1$

New class of petawatt lasers have potential for accessing and probing high energy density conditions



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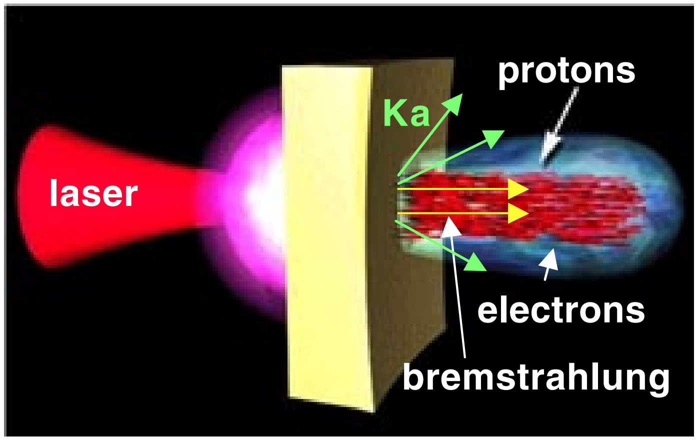

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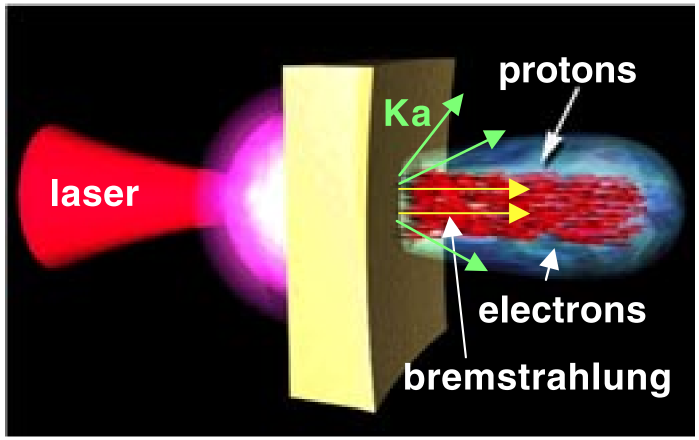
I ~ 10^{19} W/cm^2 → Mev Bremstrahlung

I ~ 10^{20} W/cm^2 → Mev protons, 400 MG, pair production

New class of petawatt lasers have potential for accessing and probing high energy density conditions



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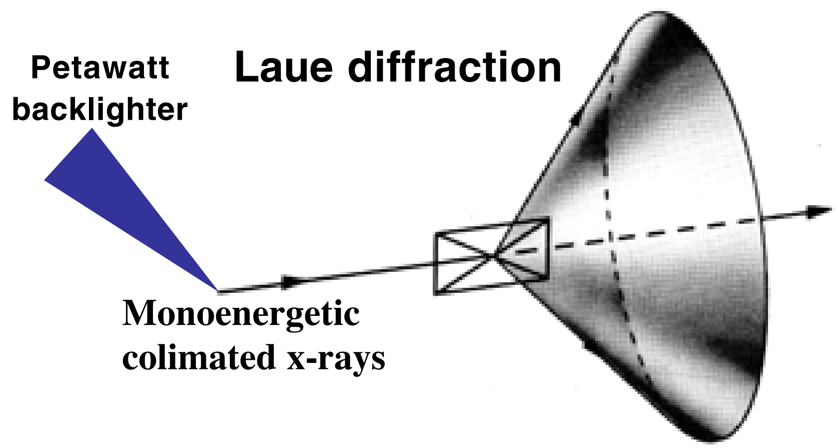
I ~ 10^{19} W/cm^2 $\longrightarrow$ Mev Bremstrahlung

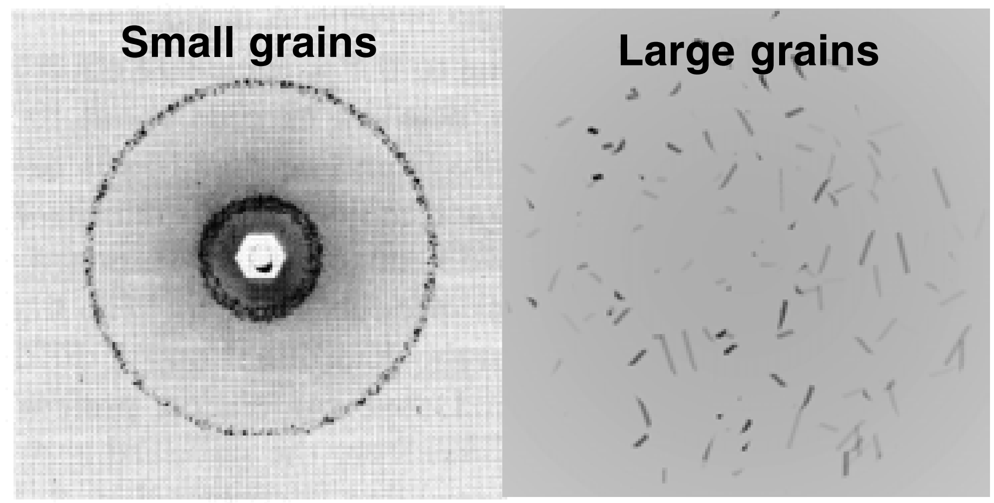
I ~ 10^{20} W/cm^2 $\longrightarrow$ Mev protons, 400 MG, pair production

I ~ 10^{24} W/cm^2 $\longrightarrow$ Nuclear reactions

High photon energy and proton probing of high energy density conditions is possible

- **20-100 keV Ka can be used to measure grain size and phase of solid material at high compression**





Borshesi, Phys Plas, 9, 2002

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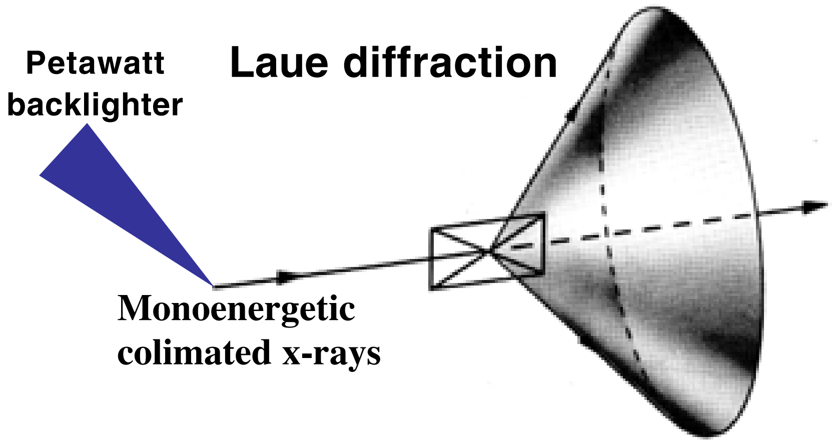
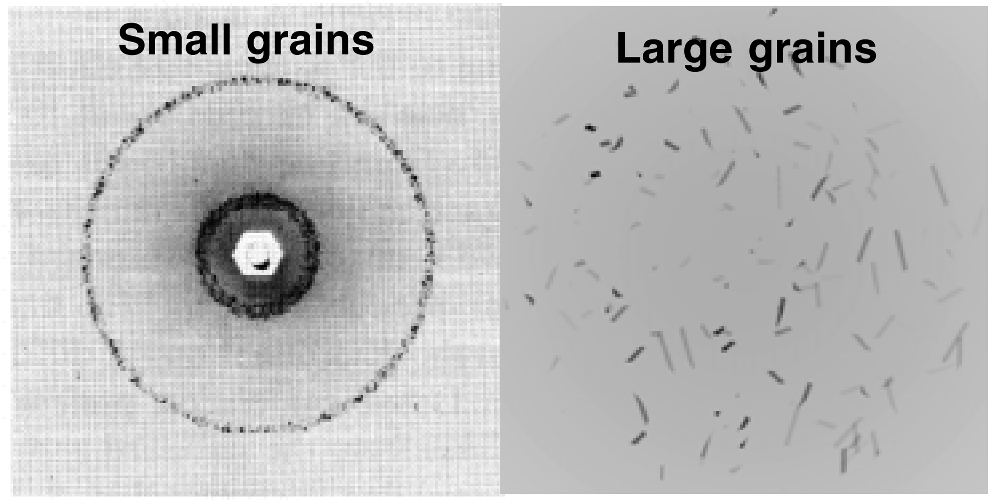
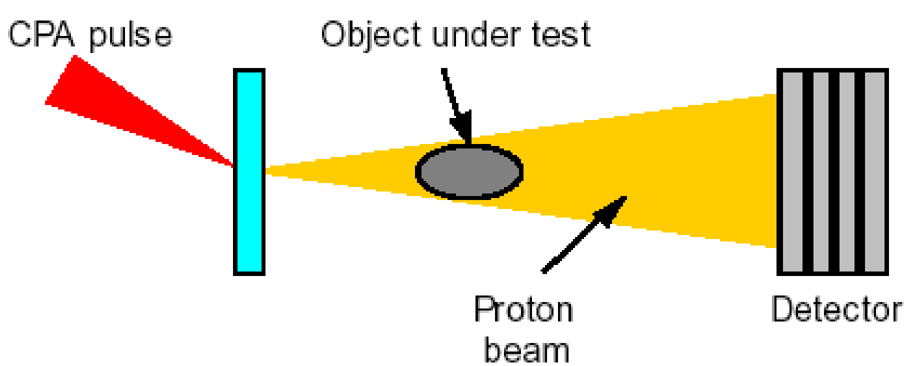
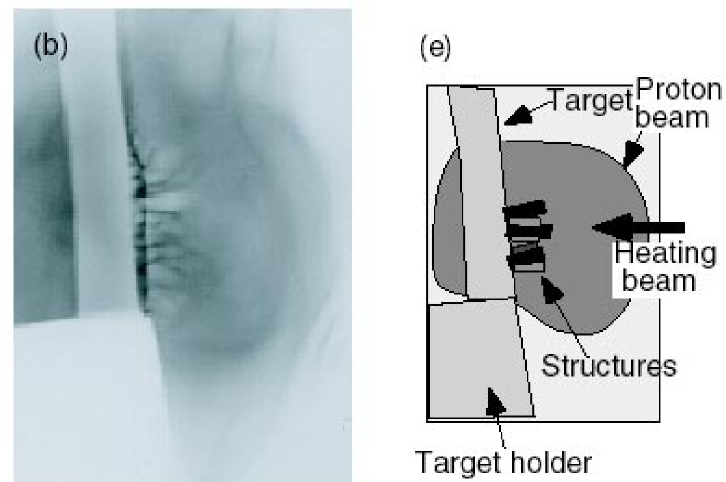




•Proton imaging:

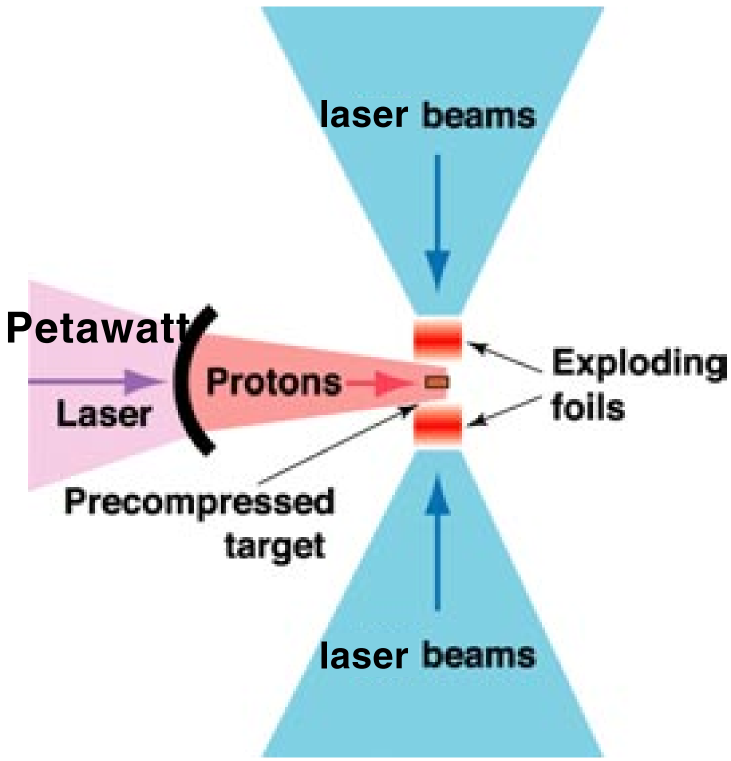


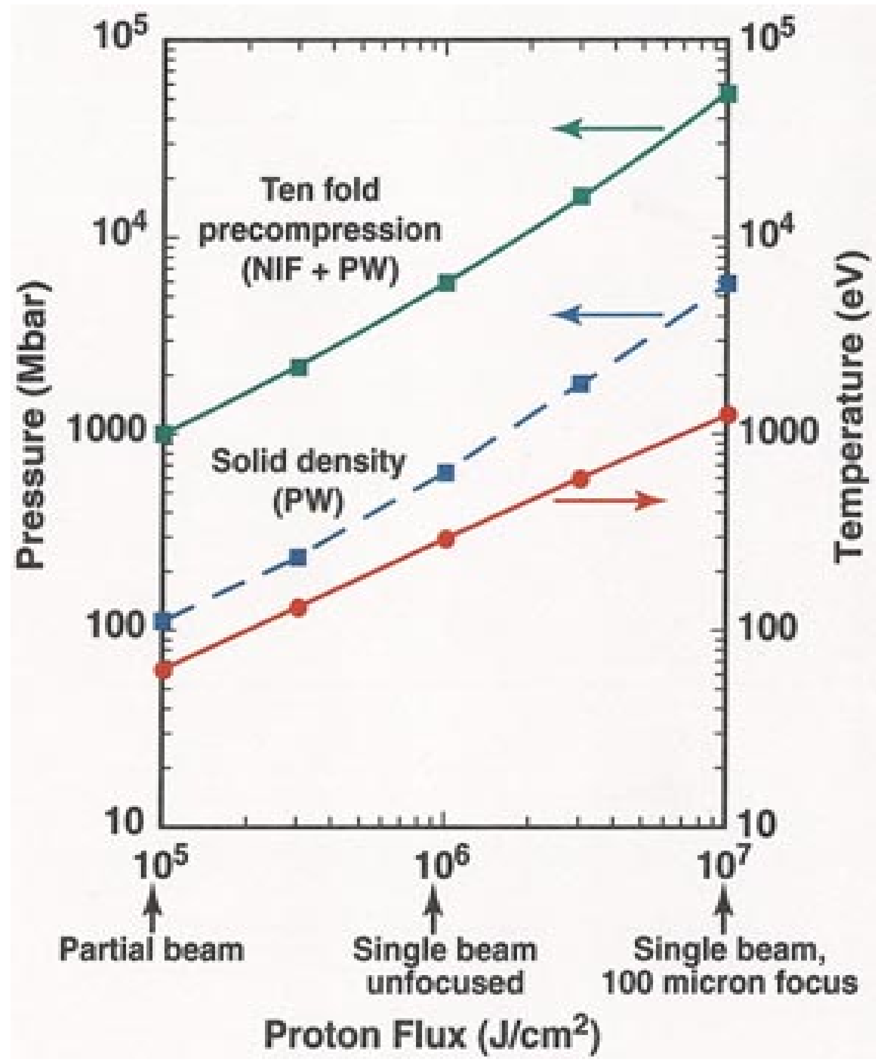


Borshesi, Phys Plas, 9, 2002

Electric fields

The capability to independently compress and heat can expand the regimes for EOS and opacity measurements



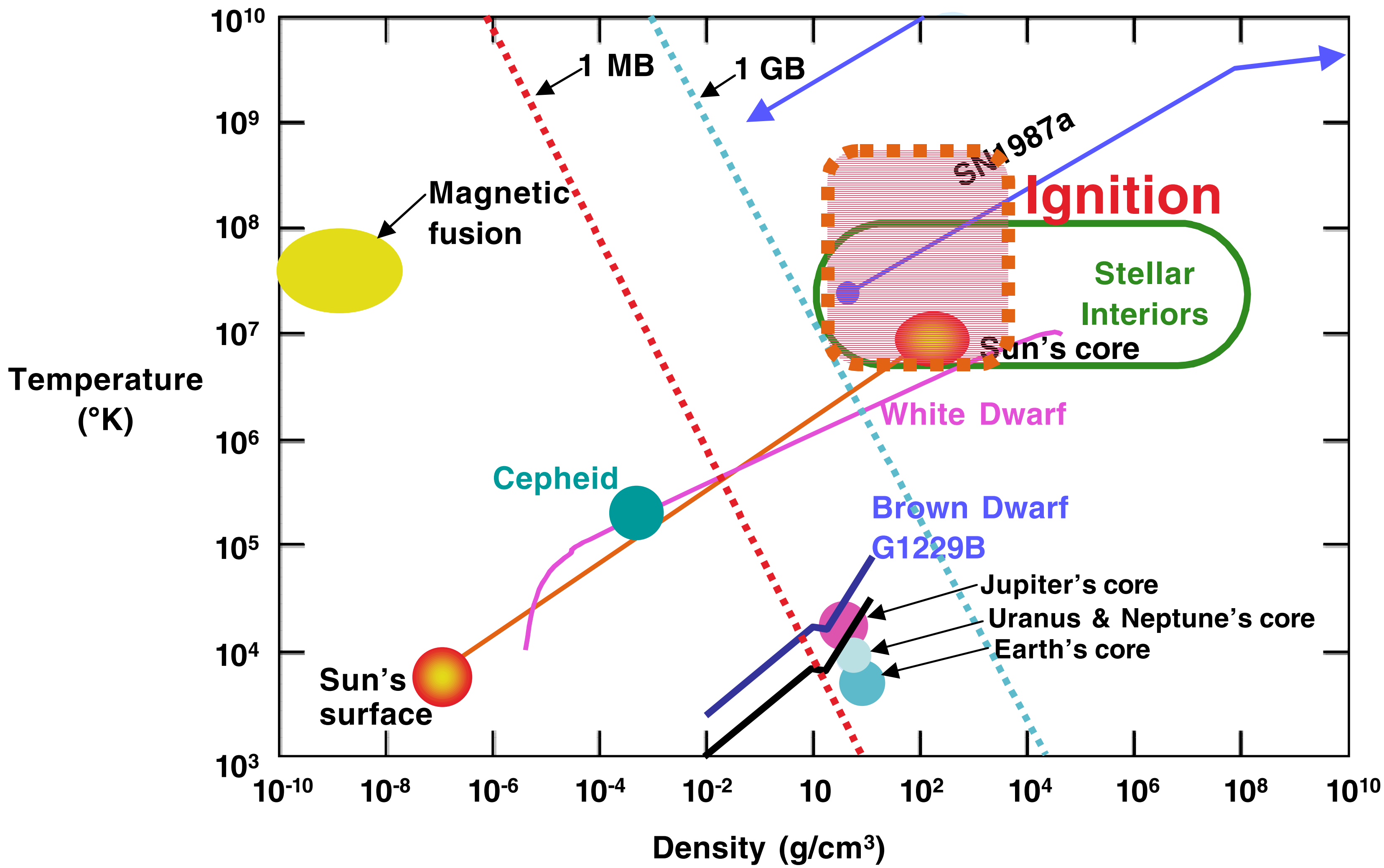


Long pulse lasers are used to precompress a material

Ion and electron beams can potentially heat materials uniformly to high energy density

Future

In burning capsules, thermonuclear reaction rates in stars may be studied



Summary

- **Significant advances in high energy density physics have occurred over the last six years**
- **The ability to make precise measurements in new regimes allows comparion with models**
  - *Hugoniot equation-of-state*
  - *Materials science at high pressure*
  - *Hydrodynamics*
  - *Radiation transport*
- **New facilities will expand access to high energy density regimes**

Recommendation from NRC report

Connecting Quarks with the Cosmos:
Eleven Science Questions for the New Century

"Discern the physical principles that govern extreme astrophysical environments through the laboratory study of high energy density physics… The field is in its infancy… "